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7/25/68

A HUMAN PERFORMANCE TRACKING SYSTEM

A THESIS

Presented to

The Faculty of the Division of Graduate

Studies and Research

by

Christopher Heddens Morgan

In Partial Fulfillment

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A HUMAN PERFORMANCE TRACKING SYSTEM

Approved:

Chairman

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Second, I wish to thank Dr. Riche and the Psychology Department for allowing me to use the hand controllers incorporated in this system. I hope that continued cooperation may result in fruitful interdisciplinary research between the two schools.

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Finally, thanks go to Peggy Green, my typist, for her cooperation, and to Diane Everett who proofread and was sweet.

A special note of appreciation goes to Dr. Callahan. His constant friendship and encouragement gave me the confidence and desire to stay at Georgia Tech for my Master's degree.

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SUMMARY

The purpose of this study is to design and construct a system to measure and demonstrate the tracking capabilities of a human operator. This system can be used for (1) research in the area of tracking and (2) demonstrations in classes discussing performance of the human operator. The tracking situation would involve an operator who manipulates either an isometric or displacement type joystick hand controller. The operator's task is to match his controlled output response, a signal on an oscilloscope display, with another similar signal which is controlled by an independent source. An alternative to this task is to have a single dot on the display which indicates the matching error between the two signals, but without displaying the signals themselves. The heart of the design involves the use of an analog computer which generates input signals, simulates a system to be controlled, and also provides statistical information on the accuracy and precision of the operator's tracking performance.

The thesis provides a functional description of the system and its components. It also provides detailed instructions concerning the operation and use of the system. This thesis, along with the manufacturer's instructions for the analog computer, provide sufficient information for almost anyone to set up and use the tracking system.

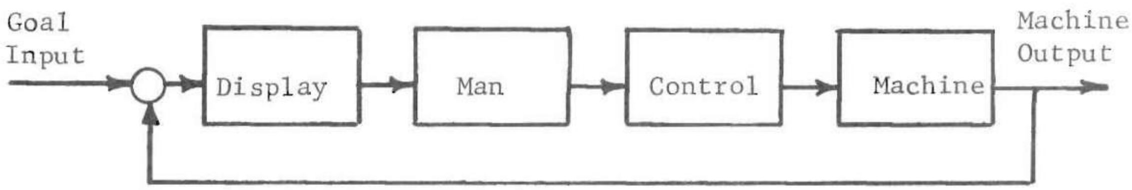
CHAPTER I

STATEMENT OF THE OBJECTIVE

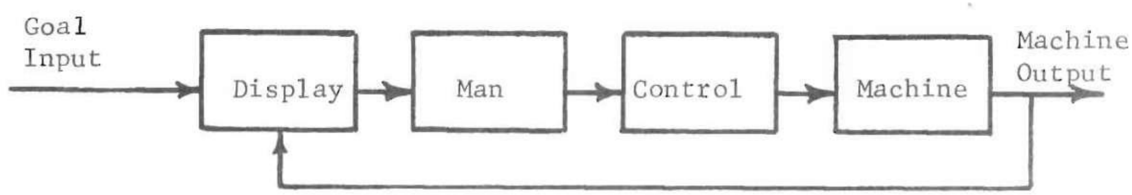
This thesis presents the design of a man-machine system which enables the demonstration as well as the experimental study of selected aspects of human tracking behavior. The design involves the integration of several electronic and electro-mechanical components with a Donner 3400 analog computer. The resulting system and its capabilities are described in detail, and instructions for utilizing the system in its various capabilities are presented. The purpose of the combined effort is to produce a tracking system with documentation on its operation and use.

Because of the increasing interest of the faculty in the School of Industrial and Systems Engineering and in the School of Psychology, Georgia Institute of Technology, in the area of human factors engineering, and, more specificially, in the area of tracking, it was decided to construct this system. The use of the system would be for (1) demonstrating tracking in classrooms and (2) conducting research in the area of tracking.

The basic tracking situation which this system simulates is illustrated in Figure 1. The input is a criterion or target which the man-machine tracking system is to acquire and maintain with some specified degree of accuracy. Information concerning the state of the machine is being fed back to the operator via the display in one of two ways, as indicated in Figure 1. Thus, information on the target being sought and



a. Compensatory Display Tracking Control.



b. Pursuit Display Tracking Control.

Figure 1. Closed Loop Manual Control Tracking Systems.

and the present state of the machine is being presented to the human operator in the system.[1]

The requirements used for designing and building the tracking system developed for this thesis are as follows:

1. The system shall simulate the tracking system illustrated in Figures 1a. and 1b. and in either one or two dimensions.

2. The desired state of the controlled machine, displayed as a target, shall be a generated input signal function. This input function shall be in the form of a dc voltage which is compatible with the analog computer and with the display used. The function generator shall be capable of generating at least the following types of functions: (1) step, (2) ramp, (3) exponential, and (4) sine. (See Figure 2.)

3. The display shall be such that it may function in two modes: First, (see Figure 1a.) the display shall present analog information about either one or two dimensions of the state of a machine <u>relative</u> to its desired state. This information, in other words, indicates the difference between desired state and current state of the machine being controlled. Second, (see Figure 1b.) the display shall also be capable of presenting analog information about either one or two dimensions of both the state of a machine and its desired state. The display of the desired state in this latter case, called the target, shall be easily distinguished from the display of the state being controlled, called the cursor.

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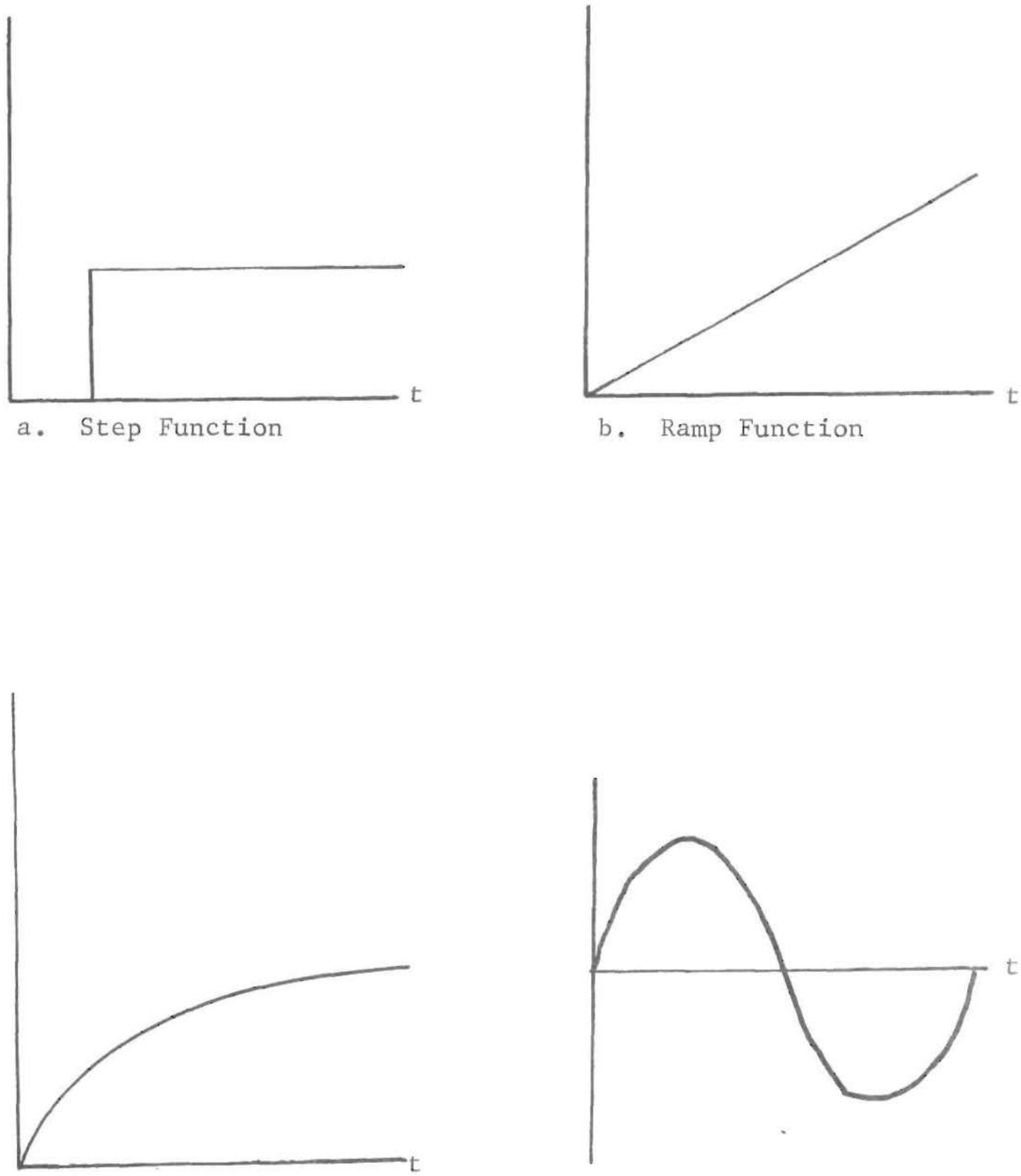
1. McCormick (2), DeGreene (1), and Morgan (3) discuss more fully the nature of the tracking situation.



a. Step Function

b. Ramp Function

c. Exponential Function

d. Sine Function

Figure 2. Functions Which May be Used as Inputs for the Target in the Tracking System.

4. The controller shall be a two dimensional joystick type hand controller compatible with the Donner Model 3400 analog computer.

5. The machine in the tracking system is to be a simulation of an input-output relationship of a dynamic system. The input, a voltage from the controller, and the output, also a voltage, shall have at least the following type relationships: position-position, position-velocity, position -acceleration, and so forth, for control of higher order derivatives; and relationships with more than one of the derivatives of the machine output state being controlled,[2] such as position-(position and velocity).

6. The measurement of the performance of the operator in this tracking system shall be a function of the error, e(t), between the target and the cursor. The types of performance measurement shall be (1) average error, (2) mean value of the error, (3) mean square error, and (4) time on target.

---

2. This kind of control is called "aided control."

CHAPTER II

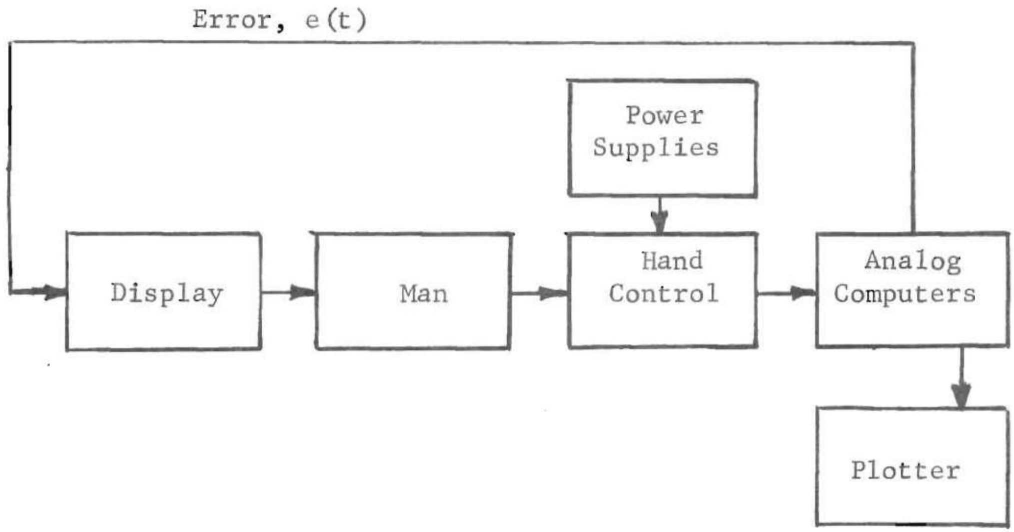
DESCRIPTION OF THE SYSTEM

The nature of the tracking system designed for this thesis will be discussed in this chapter. The block diagrams in Figures 3a. and 3b. illustrate the pieces of equipment and their relationships. While the block diagrams in Figures 1a. and 1b. show the functions represented in general tracking situation, Figures 3a. and 3b. show the specific hardware configuration used to simulate that process.

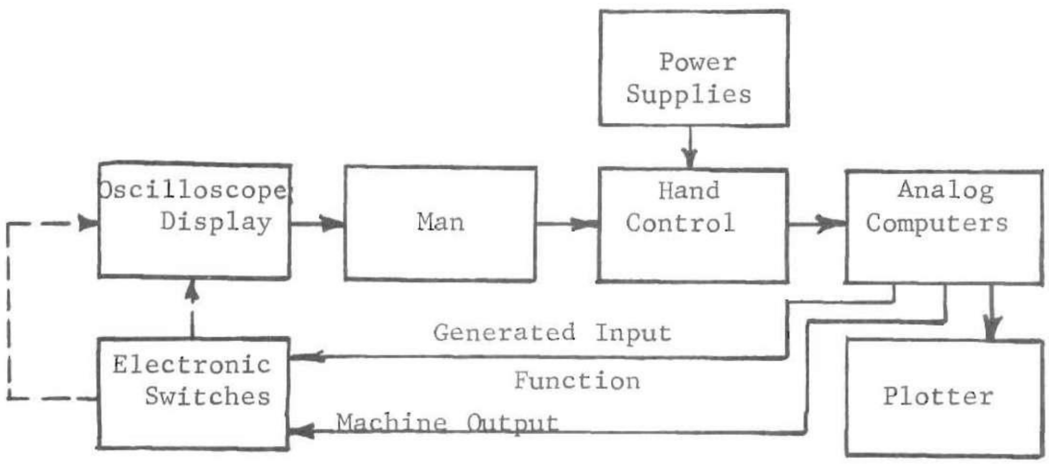
The hardware in the system may be classified into three groups: first is the display group consisting of the oscilloscope and electronic switches, second is the controller group consisting of the controller and the power supplies, and third is the analog computer group consisting of the two analog computers.

Display

The display provides the information about the desired and current state of the machine in the tracking system. The two basic kinds of displays are pursuit and compensatory. Pursuit displays show both the input target and the state of the machine being controlled. The operator's task in this case is to match the signals being shown. On the other hand, compensatory displays only have one signal. This signal is the amount of error between the input signal and machine state signal. In this situation the operator's task is to keep the signal as close to zero as possible. No information is provided in



a. Compensatory Display Tracking System.



b. Pursuit Display Tracking System.

Figure 3. Equipment Configuration for Tracking System.

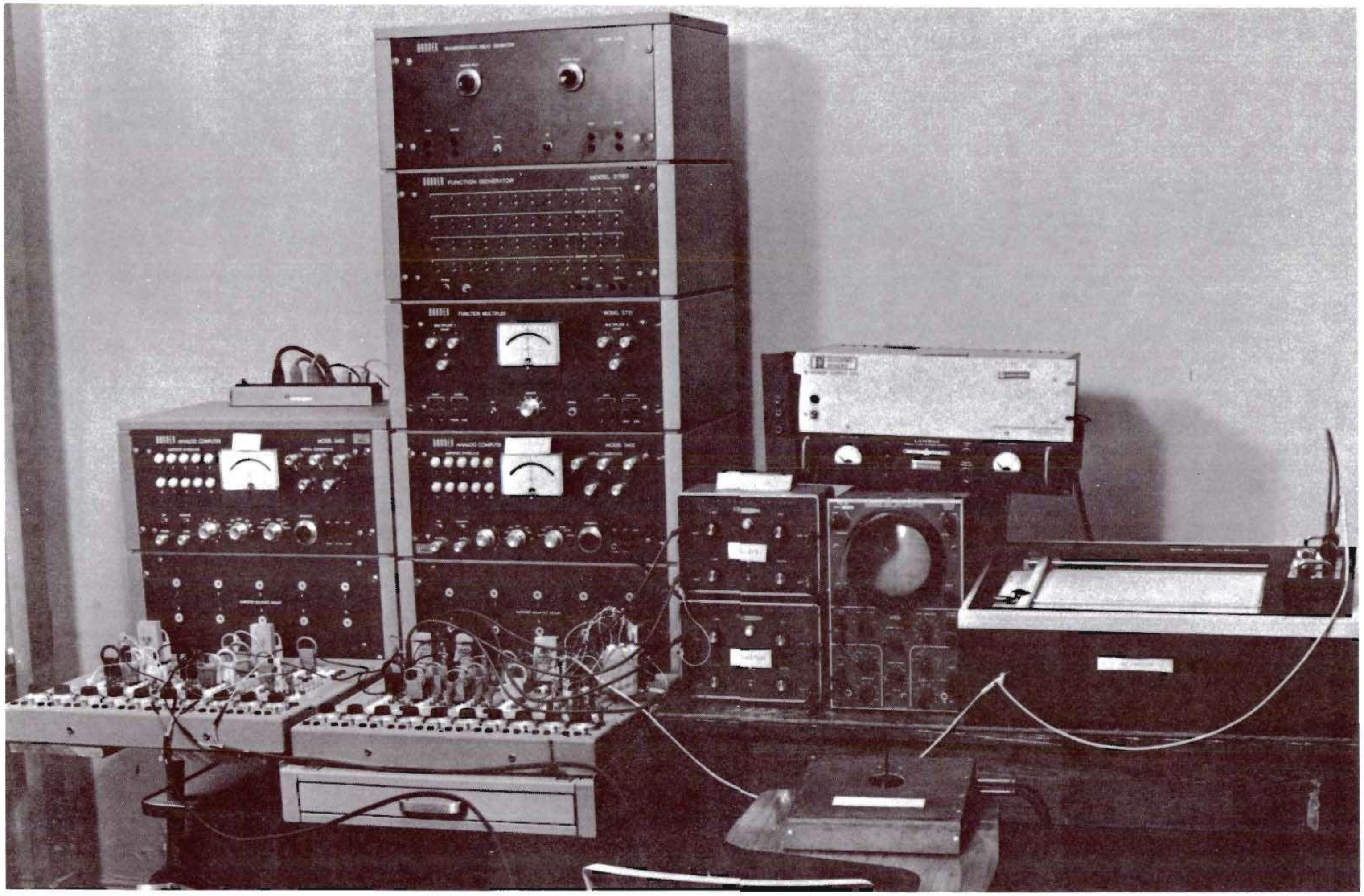


Figure 3c. Tracking System.

compensatory display tracking as to the actual state of the macine being observed and controlled. Only the difference between desired and actual performance is shown.

There are many ways of displaying information to a human operator in a tracking system (1)(2)(3). Visual displays may consist of dials, pointers, lights, cathode ray tubes, pictures, graphs, signs, and written messages. However, for this system a cathode ray tube oscilloscope is used as the display.

The oscilloscope used has a single beam, without any internal capability of displaying more than one signal on the screen. However, in pursuit display tracking the display must have the capability of showing two signals, with external control over these signals in both the horizontal (x) axis and the vertical (y) axis. Thus, it is necessary to design the equipment to alter the oscilloscope so that two signals could be independently displayed. In addition, it was found necessary to alter one of the displayed signals, the target, such that it could be distinguished from the cursor.

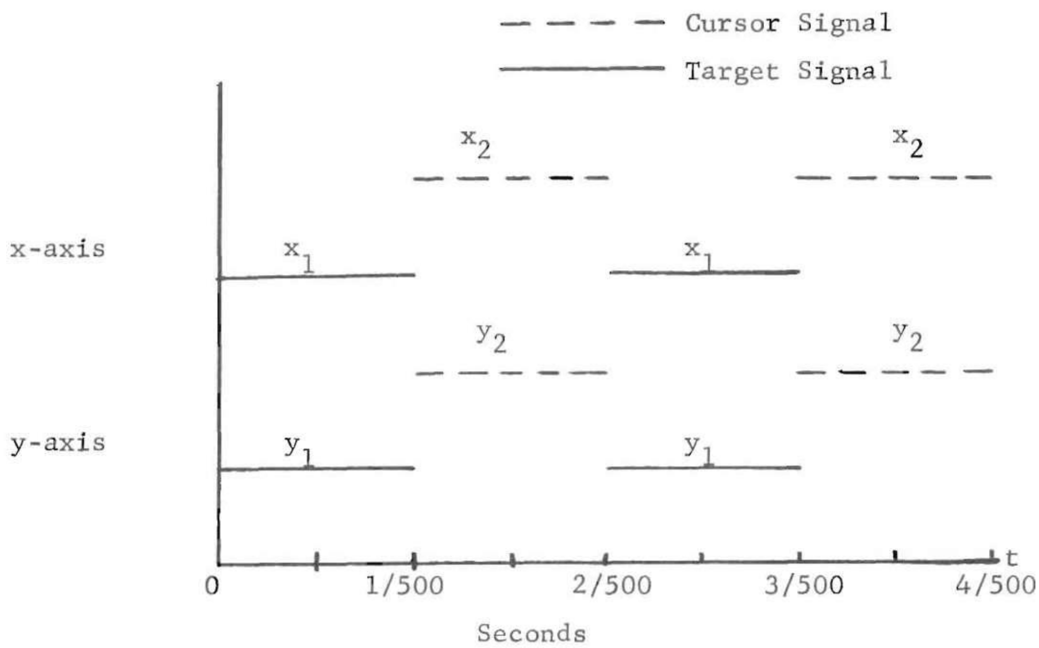
The desired results were achieved by (1) time-share multiplexing the oscilloscope beam in both the x and y axes for the <u>effect</u> of having two independent beams, and (2) superimposing a small signal on one of these beams to make it distinguishable from the other. The devices used to multiplex the beam were two Heathkit Electronic Switches connected, for synchronization, such that one unit was a master and the other a slave. There is still only one beam on the oscilloscope but this beam is being used by two input sources. For 1/500 of a second one input source controls the x and y coordinates of the beam.

For the next 1/500 of a second the other input source controls these coordinates. Then control is switched back to the first input source and so on. While there is still only one beam, it appears as if there are two beams because the switching rate is so fast.

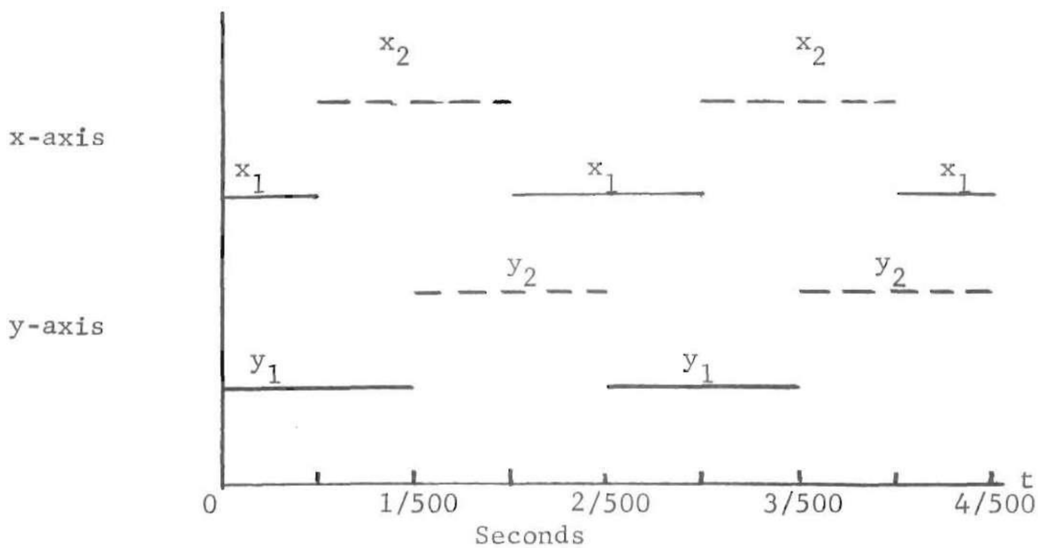
The reason for having two multiplexors is to share the x coordinate input to the oscilloscope with one multiplexor and to share the y coordinate input to the oscilloscope with the other. The important thing in this process is that the input x_1 and the input y_1 control the x and y coordinates during precisely the same time intervals. Without this synchronizing, the beam would display x_1 with y_2 and x_2 with y_1 as well as x_1 with y_1 and x_2 with y_2. Figure 4a. shows the oscilloscope output display with proper synchronization. Figure 4b. shows the result of not synchronizing the switching.

In order to distinguish the cursor from the target, a 60 cycle signal of variable amplitude was superimposed on the x axis component of the target signal,and a similar signal about 90^o out of phase was superimposed on the y axis component of the target signal. This causes the target signal to be displayed as a small circle of variable diameter. Actually, the target is more like an ellipse, however the effect is still the same.

The electronic switches are not needed when a compensatory display is wanted. Compensatory tracking, it is recalled, only requires a single displayed signal, e(t), and the signals are fed directly from the analog computer to the oscilloscope display.



a. Sychronized Time Sharing
of Oscilloscope Beam.

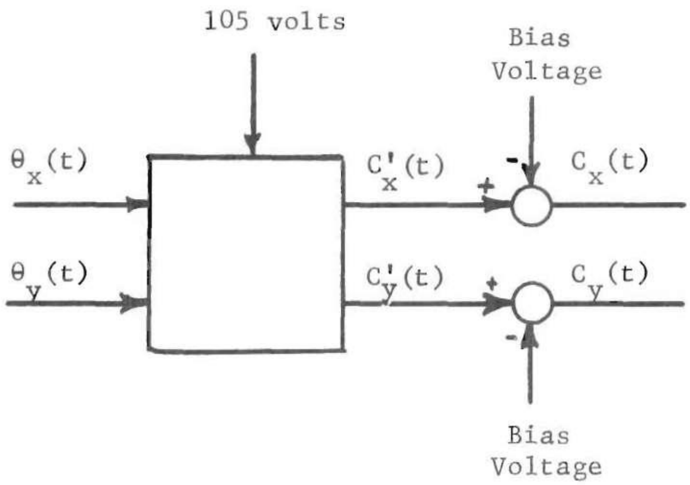


b. Unsynchronized Time Sharing
of Oscilloscope Beam.

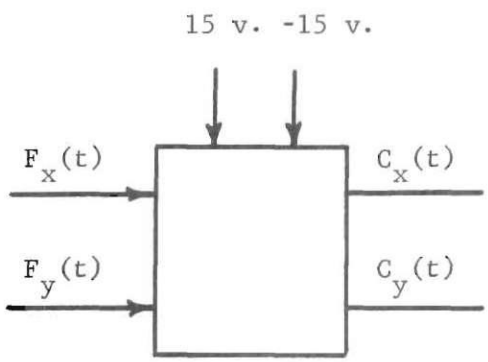
Figure 4. Time Share Multiplexing of a Single Beam Oscilloscope for Pursuit Display Tracking.

Controllers

The two controllers used in this system are a displacement and an isometric controller. The displacement controller consists of two potentiometers in a gimbled enclosure such that movements in two dimensions may be made. One potentiometer registers movements left and right while the other registers movements forward and backward. The joystick moves easily and with no spring or damping forces. The human operator input to the controller is a movement of the joystick about a fixed point. From a neutral (vertical) position this joystick may be rotated a maximum of 60^{o} forward or 60^{o} backward and 60^{o} left or 60^{o} right. The forward-backward movement is an input represented by an angular displacement Θ_x with the corresponding output being a voltage C_x'. The left-right movement is an angular displacement Θ_y with C_y' being the output voltage. In Figure 5a. the controller is represented in block diagram form. The power input of 105 volts is represented by the arrow into the top of the box. This voltage input is the passive input acted upon by the angular displacement movements of the joystick. The output voltages, $C_x'(t)$ and $C_y'(t)$, are in a positive range (about 12-22 volts). This fact necessitates the use of a bias voltage such that the range is made to be symmetric about zero (about -5 to 5 volts). In this way the operator has the ability to (1) provide a positive input to the controlled machine, (2) no input control, or (3) a negative input control. By being symmetric about zero, the maximum amount of positive control is the same as the maximum amount of negative control. Of course, this biasing procedure may be changed to fit the type of control it is wished to simulate. For instance, it may be the case where the maximum



a. Displacement Controller and Bias Circuit.



b. Isometric Controller.

Figure 5. Block Diagram of Joystick Controller Inputs and Outputs.

positive control is desired to be greater than the maximum negative control.

The isometric controller operates on an entirely different principle. The difference lies with the F_x and F_y inputs, shown in Figure 5b., which are forces in the x and y directions, respectively. The output, however, is a dc voltage just as with the displacement controller. The passive inputs are voltages of +15 volts and -15 volts supplied by two power amplifiers.

The isometric controller has an internal circuit which performs the function of making the output symmetric about zero. Thus, there is no need for using a bias as with the displacement controller. However, this also means that the isometric controller cannot be adjusted to give more control to the positive side on a particular axis and still have a neutral (zero) output when no force input is being applied.

Analog Computer

The analog computer is at the heart of the tracking system.[3] Unlike the other pieces of equipment it performs multiple functions. As can be seen in Figure 3, these functions are: (1) generating the target input function used for the display as well as for arriving at the error function, e(t), (2) simulating an input-output characteristic of a machine, and (3) calculating the performance statistic to be fed to the X-Y recorder.

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3. References (4), (5), and (6) contain more detailed explanations of the general nature of the analog computer.

Input Function Generation

The input function to the tracking system is a simulation of the target path. This input may take the form of some complex function or one of a few simple test functions. Figure 2 illustrated the basic input functions which are typically used in the analysis of feedback control systems.

The input function is one of the most important variables in the system. For instance, varying the frequency of a sine wave input would yield information on how an operator responds at different frequencies. Clearly, it is more difficult to react to very high frequencies than it is to low frequencies (3). Also, the amplitude is an important factor. If displayed amplitudes are very low, the operator is not likely to react as quickly or as accurately than if the displayed amplitudes were large and easily detected (3).

Four ways input functions can be generated are as follows: (1) using the analog computer, (2) manually manipulating a joystick and using the output as an input, (3) generating a signal on an electrical signal generator, or (4) recording a function generated by any of the preceding three means on an FM tape recorder and playing it back. Only the first two methods are presently available in the designed tracking system; however, the latter two methods will be discussed in the last chapter of this thesis.

Programming Control Order of Simulated Machine

This function of the analog computer is involved with the simulation of the particular machine input-output relationship desired in the control system.[4]

The most basic types of machine input-output relationships are those in which the input is an *n*th order derivative of the output. Control of such a machine is called *derivative control*. For example, a system employing second order derivative (acceleration) control has a machine whose output is a double integration of its input. On the oscilloscope display, this machine output is represented by a signal, and changes in position of this signal are made by causing changes in its acceleration. Thus, the position is not controlled directly. Rather, it is through controlling the acceleration that changes in position may be made. Of course, it is possible to have the simplified situation in which position may in fact be directly controlled. Such control is called zero order derivative control.

A slightly more sophisticated version of derivative control involves the control of more than one derivative output. That is, the operator in a control system may simultaneously, and with only one controller, influence both the velocity and acceleration of a machine output. This type of control is referred to as *aided derivative control*.[4]

Performance Measurement

The final function which the analog computer is called on to perform is that of analyzing the precision and accuracy with which the operator performs the tracking tasks.

---

4. See references (1), (2), and (3) for a discussion on machine control.

The first step in performance measurement is obtaining the error function, e(t). This function is the difference between the value of the target signal and the value of the cursor signal. It is obtained by changing the sign of the target voltage and adding it to the cursor voltage. The resultant is then manipulated, depending on the type error performance statistics desired, and plotted. It is important to note that in two dimensional tracking two error functions are used, $e_x(t)$ and $e_y(t)$.

The measurement of performance in the tracking system is one of four integrals of the error between the cursor and the target. The criteria are divided into three catagories: (1) mean of the error, (2) variance or standard deviation of the error, and (3) control limit tolerance of the error.

The first type criterion is the <u>average error</u> and is an indication of a tendency of the operator to consistently follow or lead the cursor in some way. The equation of this is

$$e = \frac{1}{T}\int_{t_0}^{t_1} e(t)dt,$$

where T is the time interval $t_1 - t_0$.

The second class of criteria include the <u>mean value of the error</u> (not the same as the above) and the <u>mean square error</u>. The equation for the mean value of the error is

$$e = \frac{1}{T}\int_{t_0}^{t_1} |e(t)|\, dt.$$

The equation for the mean square error is

$$e = \frac{1}{T}\int_{t_0}^{t_1} e^2(t)dt.$$

The third class of criteria is called time on target. This error gives an indication of the percentage of time the operator can keep the error down to some arbitrary value. The equation for the time on target is

$$e = \frac{1}{T}\int_{t_0}^{t_1} a(t)dt$$

$$a(t) = 1 \quad \text{for} \quad e(t) \leq c$$

$$a(t) = 0 \quad \text{for} \quad e(t) > c$$

where the constant c is the control limit value.

System Variables

In the set up of a demonstration or experiment several decisions must be made. Each decision constitutes the setting for one of the independent variables in the hardware configuration. Some of these variables have a limited number of possible settings, while others have an unlimited number of possible settings. These seven independent variables are briefly:

1. One dimensional tracking or two dimensional tracking.
2. Displacement joystick control or isometric joystick control.[5]

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5. If the displacement controller is selected, the voltage supply on the analog computer problem board is used instead of the external power supply shown in Figure 6.

3. Control order and associated amplifying constants.

4. Aided or non-aided tracking.

5. Choice of one of the four performance criteria.

6. Choice of input function.

7. Choice of pursuit display or compensatory display.[6]

---

6. In the case of compensatory display, the electronic switch may be eliminated from the system. In this case the signal(s) from the analog computer connect directly with the scope.

CHAPTER III

SET UP OF EQUIPMENT

The purpose of this chapter is to provide sufficient instructions for the use of the tracking system designed for this thesis. It is assumed that this will permit the use of the system with no additional information other than a working familiarity with the Donner 3400 analog computer involved.

All three functions of the analog computer are arrived at from the same building blocks. Figures 6 through 10 show these building blocks and how they are set up on the computer problem board. Beneath each set up is found the symbol of the basic function illustrated. These symbols are used in Chapter III in schematic diagrams to help explain the analog computer set ups discussed there.

The problem board of the analog computer itself consists of ten operational amplifiers, five of which may be used as integrators and all ten of which may be used for the other basic functions. A photograph of the problem board and control panel of the Donner 3400 Analog Computer is in Figures 26 and 27. The resistors, capacitors, and a typical wiring set up can be observed in this picture and related to Figures 6 through 10, as well as the other Figures which illustrate programming set ups.

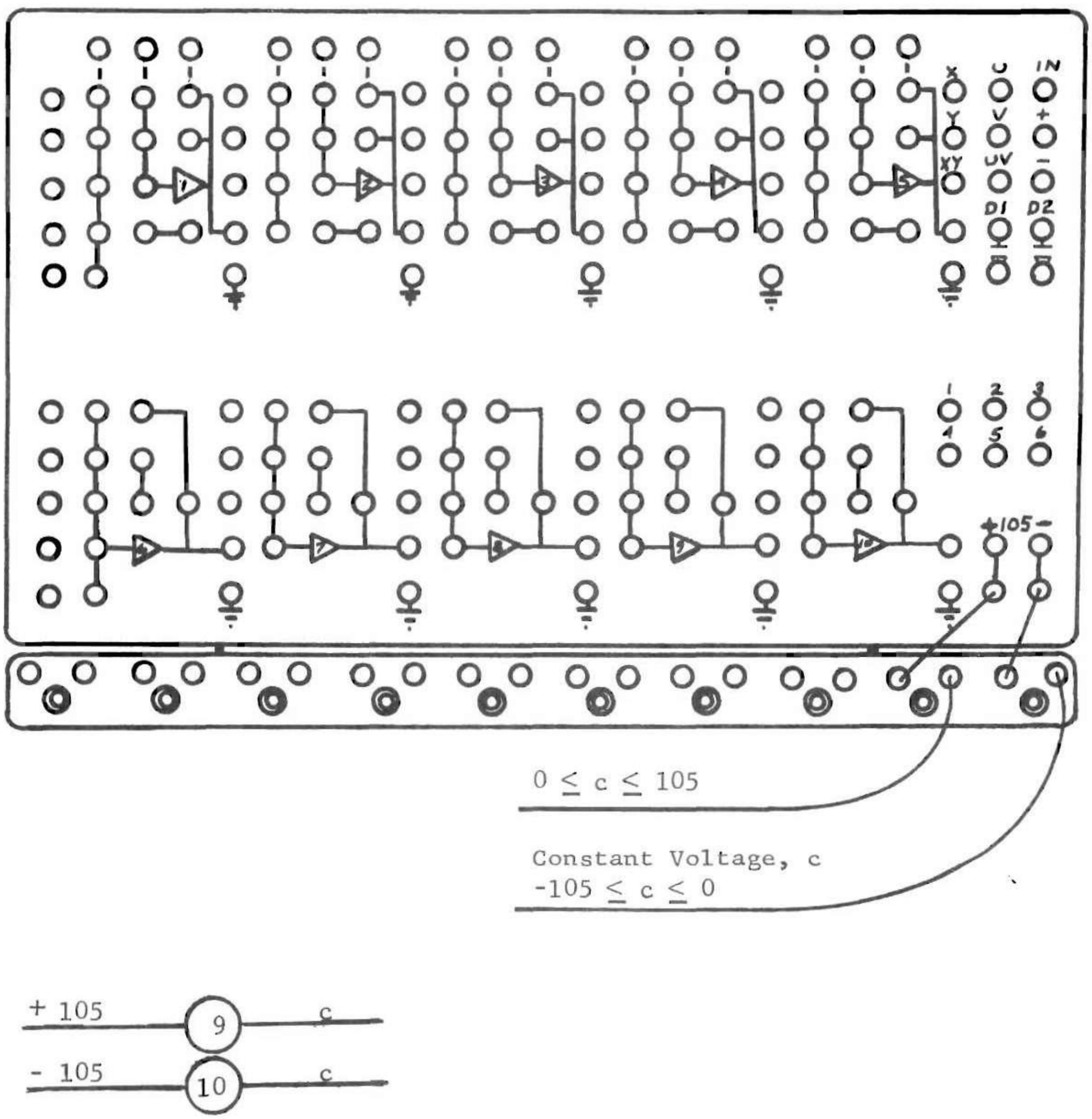
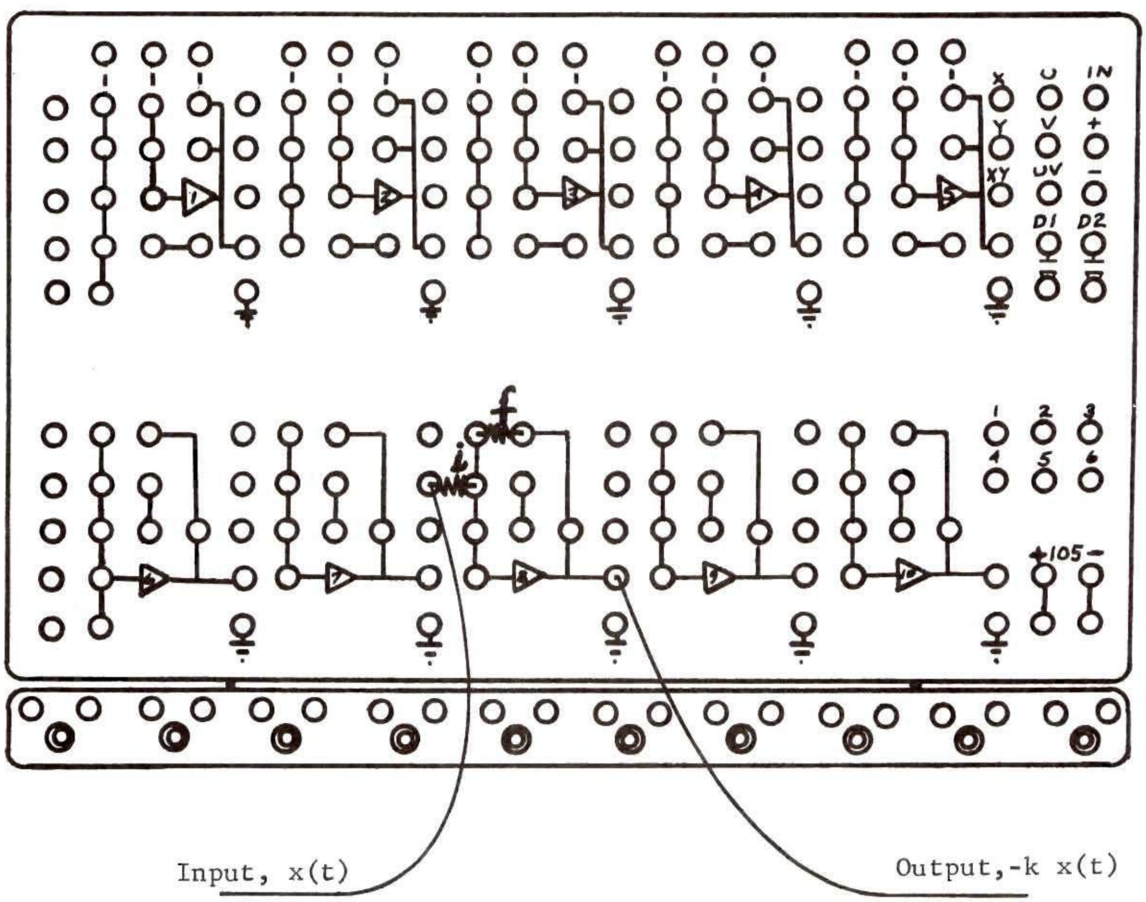


Figure 6. Constant Voltage Power Supply Function of the Analog Computer.



$$\text{Amplification} = \frac{f}{i} = k$$

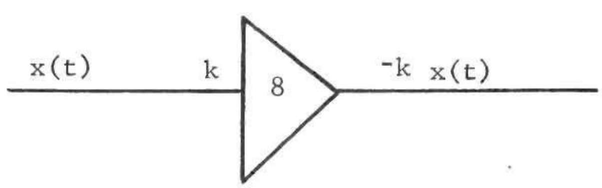
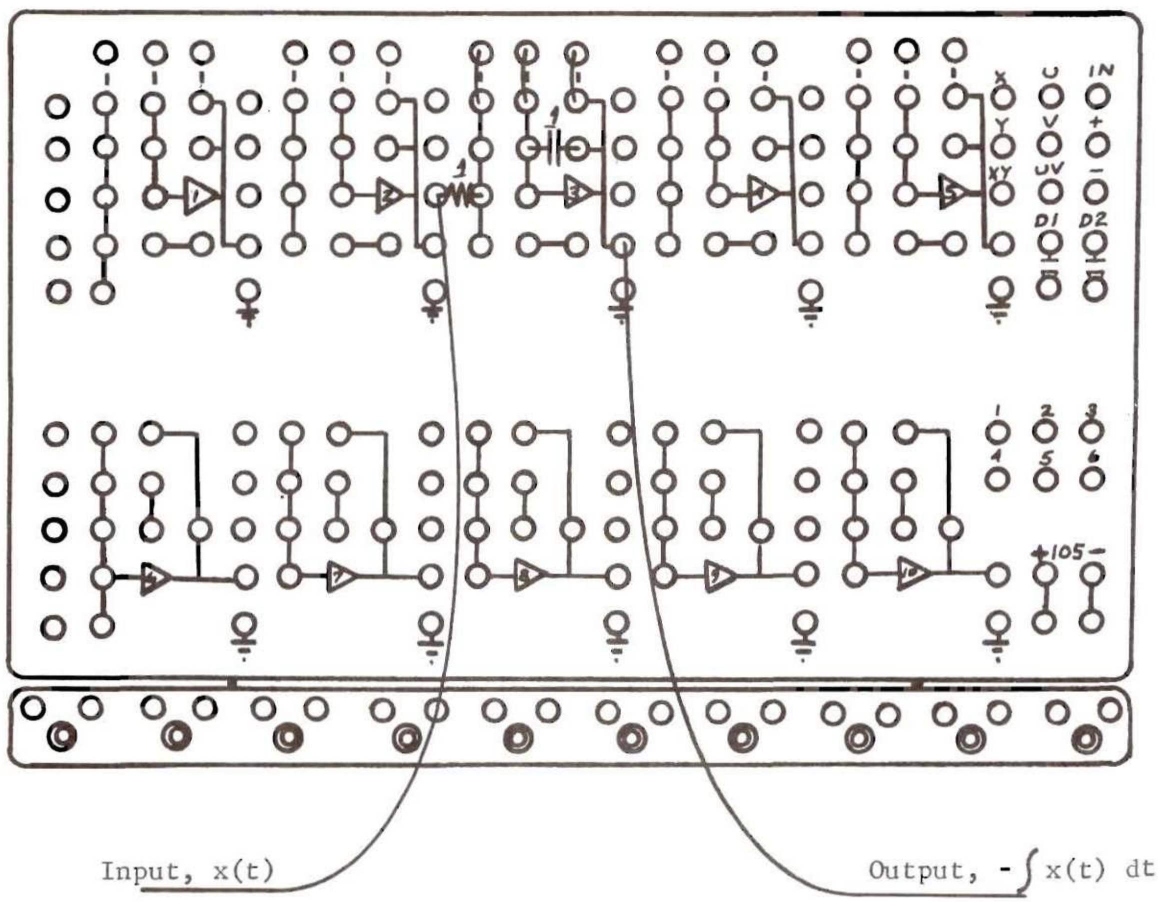


Figure 7. Amplification and/or Sign Inversion Function of the Analog Computer.



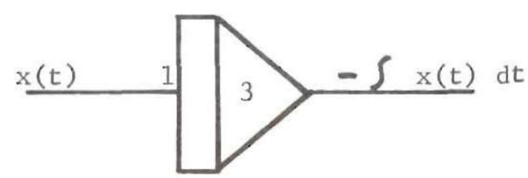


Figure 8. Integration Function of the Analog Computer.

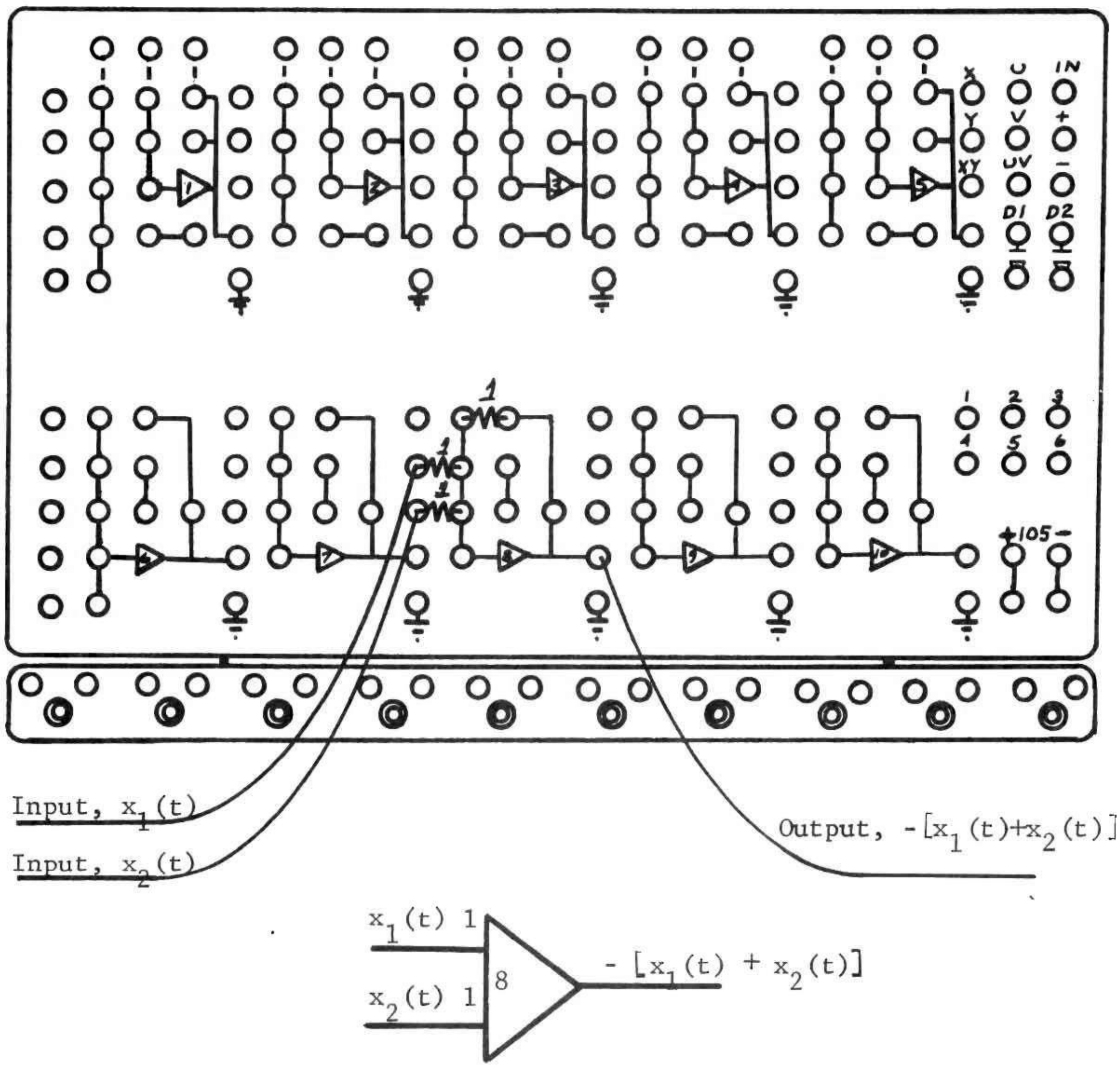


Figure 9. Summation of Two Signals with Sign Change Function of the Analog Computer.

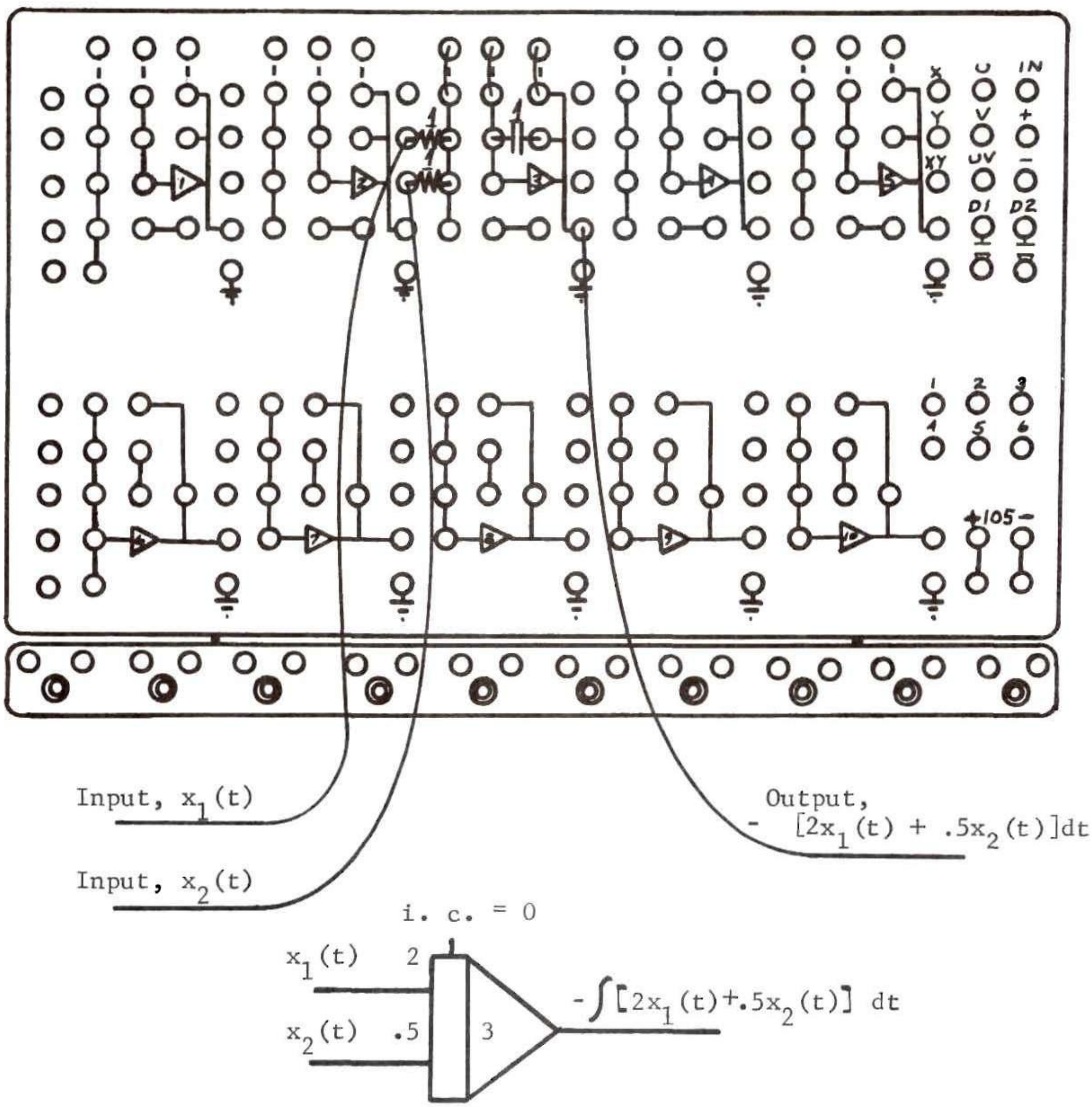


Figure 10. Amplification, Summation, and Integration of Two Signals Function of the Analog Computer.

Display

Compensatory

Compensatory display tracking, whether it be in one or two dimensions, is easier to set up than is pursuit display tracking. For this display the electronic switches are not used. The functions $e(t)$ or $e_x(t)$ and $e_y(t)$ are obtained by subtracting the input function signal from the controlled output signal. The input function signal is inverted by feeding the signal through an operational amplifier having an amplification factor of one, and then added to the controlled output signal at a summer. This output is then fed directly into the oscilloscope.

Pursuit

When using pursuit display tracking the electronic switch(es) must be used. After the switches are turned on at the beginning of a session, an important first step is to plug a 100k resistor across the output terminals for about five minutes. This procedure is essential during the warm up of the equipment in allowing a capacitor to charge up. After the warm up period this resistor should be removed.

One Dimensional Tracking. One electronic switch, the master switch of the two, is used to time share multiplex the beam of the oscilloscope and to make the target signal into an ellipsoid. The input function signal is connected to the "A" input of the switch, and the cursor signal is connected to the "B" input. The single output is then connected to the vertical input of the oscilloscope, and an appropriate scale on the scope is chosen. The horizontal sweep is placed on 60 cycles per second, and the sweep duration is adjusted for the desired diameter of the target circle. The black knob on the upper left of the switch is then adjusted to the same diameter for the vertical direction. By combining these horizontal and vertical sweeps of the signal both at 60 cycles per second, a circle, or ellipse, is formed. Next the gains on the electronic switch are set to give the appropriate setting for the display.

Two Dimensional Tracking. For two dimensional tracking, both switches are used, and it does not matter which switch is used for the vertical axis. The only difference here is that the oscilloscope horizontal axis control is placed in the "external" mode, and both horizontal and vertical input channels of the scope are used.

Hand Controllers

Displacement Controller

The displacement controller is housed in a wooden box which was designed with two connector jacks on the right side. These jacks are the three conductor type, providing connection for (1) power supply input, (2) output, and (3) ground. The jacks are labeled as either the y-axis (front-back) or x-axis connector. The cords that connect with these jacks have clearly marked plugs. However, only one cord has a ground connection since the ground in the controller is common for both x and y axes and should be used for one dimensional tracking. The plugs marked "input" are connected to the 105 volt receptacle on the computer problem board. The plug marked "output" is inserted into an appropriate resistor in one of the operational amplifier circuits. Summed with this controller output is a bias voltage of opposite sign from that of the controller voltage and having a value such that the output of the operational amplifier is zero when the joystick is in a neutral position. If no amplification of voltages is used, the range of this summer will be about $\pm$ 5 volts. Again, if only one dimensional tracking is being employed, be sure that the cord with the ground plug is used and that this plug is inserted into one of the ten ground connections on the problem board. Figure 11 illustrates the connections described.

Isometric Controller

The isometric controller has a somewhat different hookup. However, the output is already set at the proper range where zero force corresponds to zero volts output and, hence, the summer used for the displacement controller output is not needed. Also, the input differs slightly from that of the displacement controller. Because the isometric controller has a current drain too high to use the power supply voltages on the analog computer, separate power supplies are used which supply adequate current. The input voltages are +15 volts and -15 volts. The jacks associated with the power supply and plugs from the controller are clearly marked. Note that the ground connection plugs into both the power supply ground jack and an analog computer problem board ground jack.

Should the output from the controller not be zero there are two methods of correcting this. (1) There are two set screws inside the controller which may be adjusted by removing the bottom cover and inserting a long screwdriver through the two holes allowing access through the circuit boards. (2) A bias voltage may be summed with

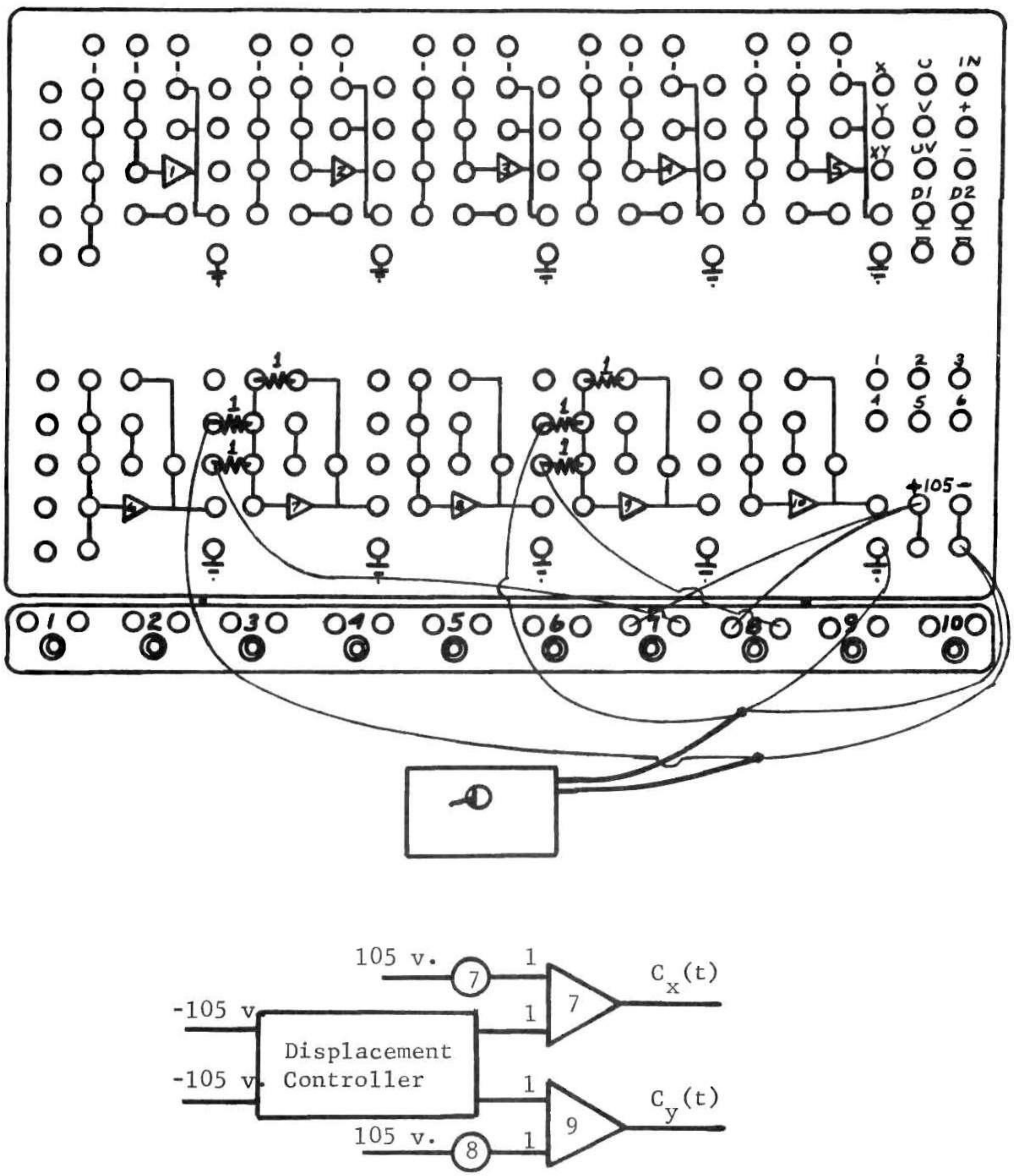


Figure 11. Displacement Controller Wiring.

the controller output as is done with the displacement controller.

Four of the five connections must be made in one axis tracking, with only the undesired output plug remaining unconnected. Figure 12 illustrates the connections described.

Input Function Generation

Ramp

The ramp function is generated by applying a constant voltage to the input of an integrator having zero initial condition as set on computer control panel. Figure 13 illustrates the wiring and gives an analog computer programming diagram of the set up.

Exponential

This function is generated by using an integrator and one potentiometer, and having a forcing function of some constant voltage applied to the integrator which has zero initial condition. The output of the integrator is fed through a potentiometer and back to the input of the integrator. The set up is identical to the ramp generator except for the feedback loop. Figure 14 illustrates the wiring.

Sine

Two integrators, one inverter, and one potentiometer are required to generate a sine function. The frequency of the sine wave is adjusted by varying the amplification of the feedback loop through the inverter and potentiometer. The amplitude is adjusted by setting the initial condition of the first integrator to the desired maximum amplitude desired. The initial condition of the second integrator is zero. Figure 15 illustrates the set up.

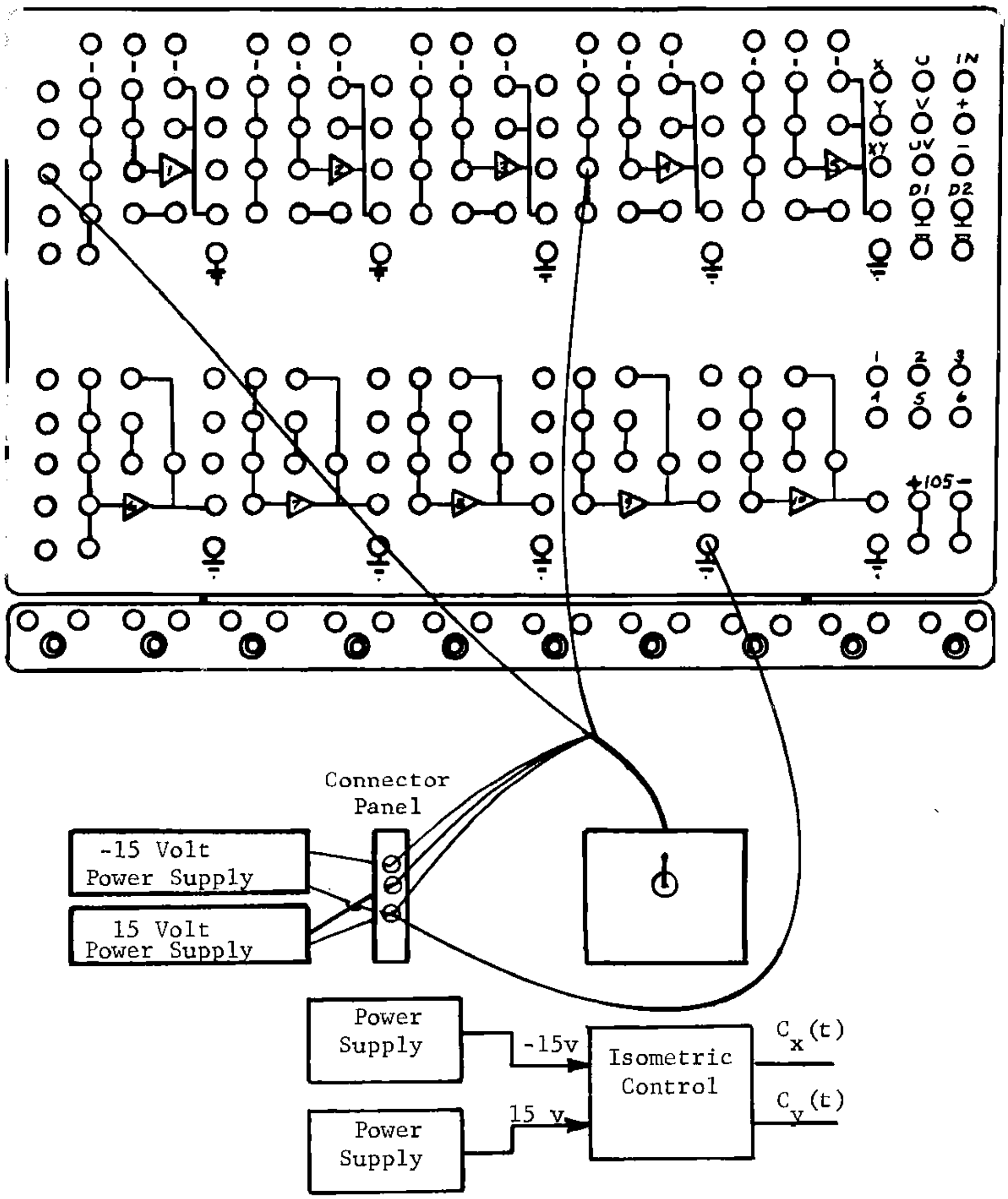


Figure 12. Isometric Controller Wiring.

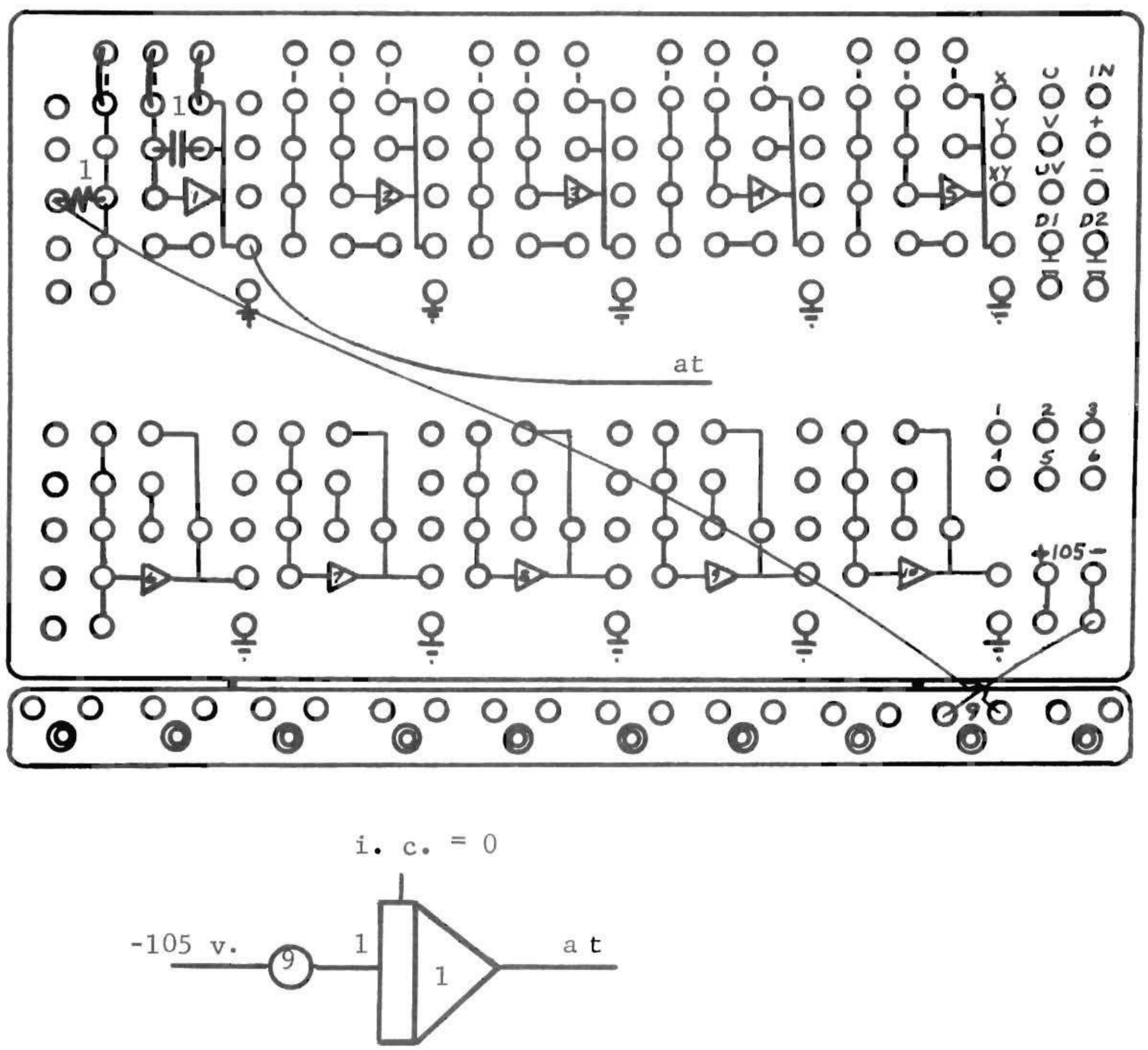
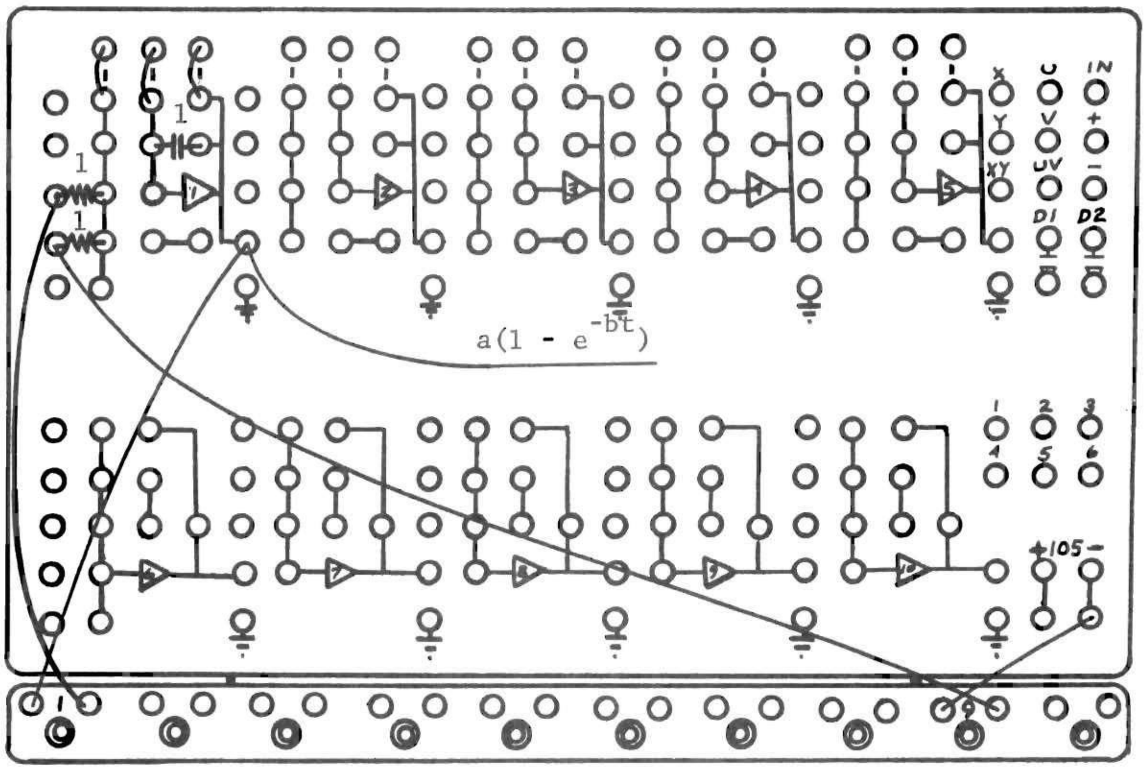


Figure 13. Ramp Function Generator Set Up.



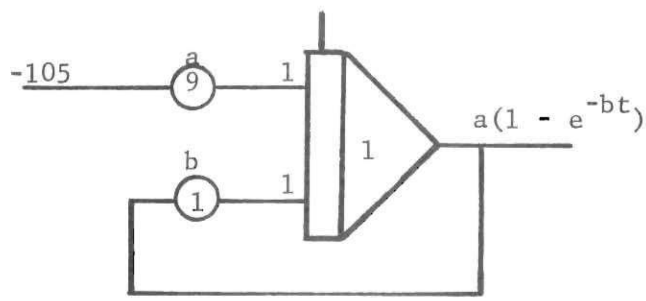
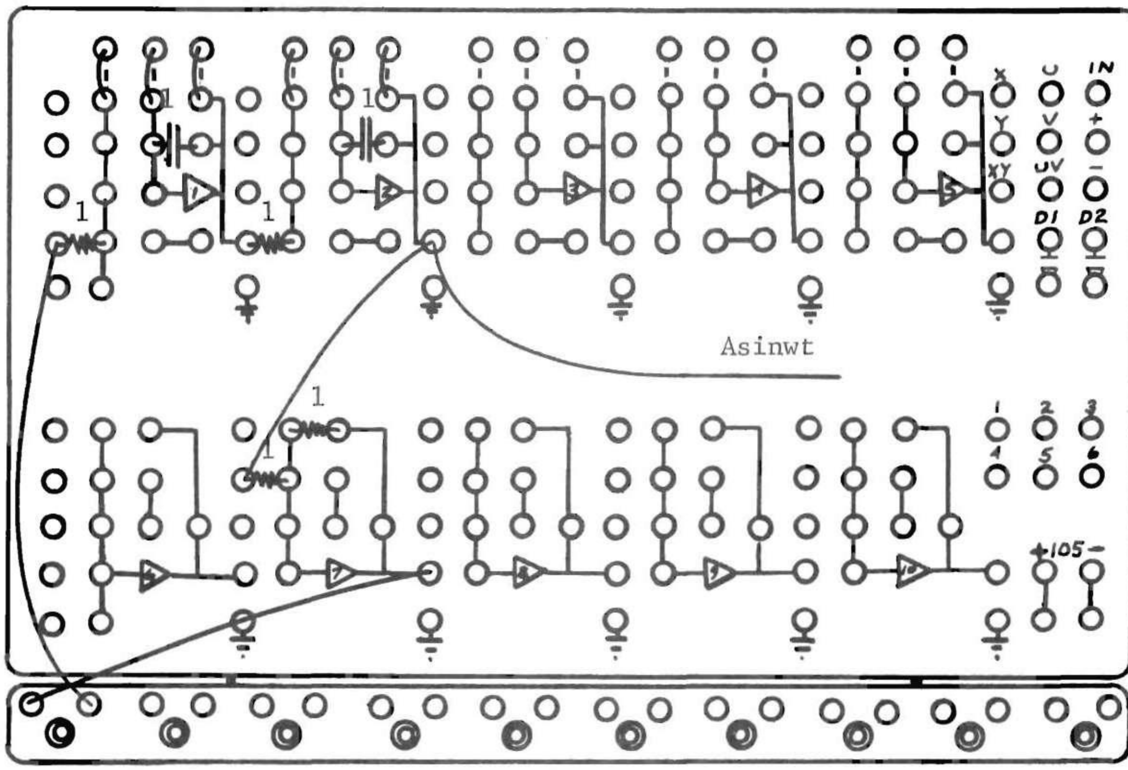


Figure 14. Exponential Function Generator Set Up.



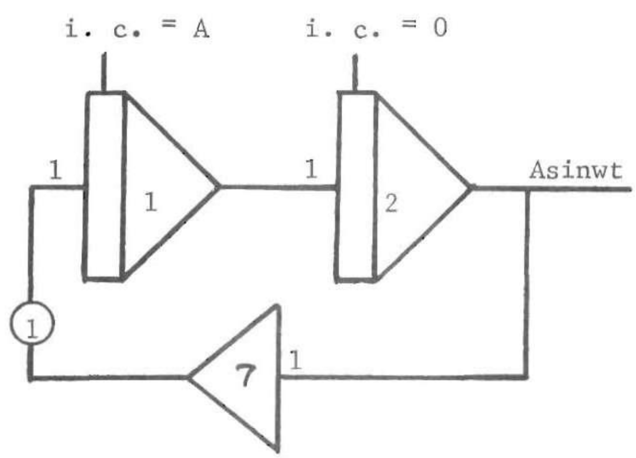


Figure 15. Sine Function Generator Set Up.

Damped Sine

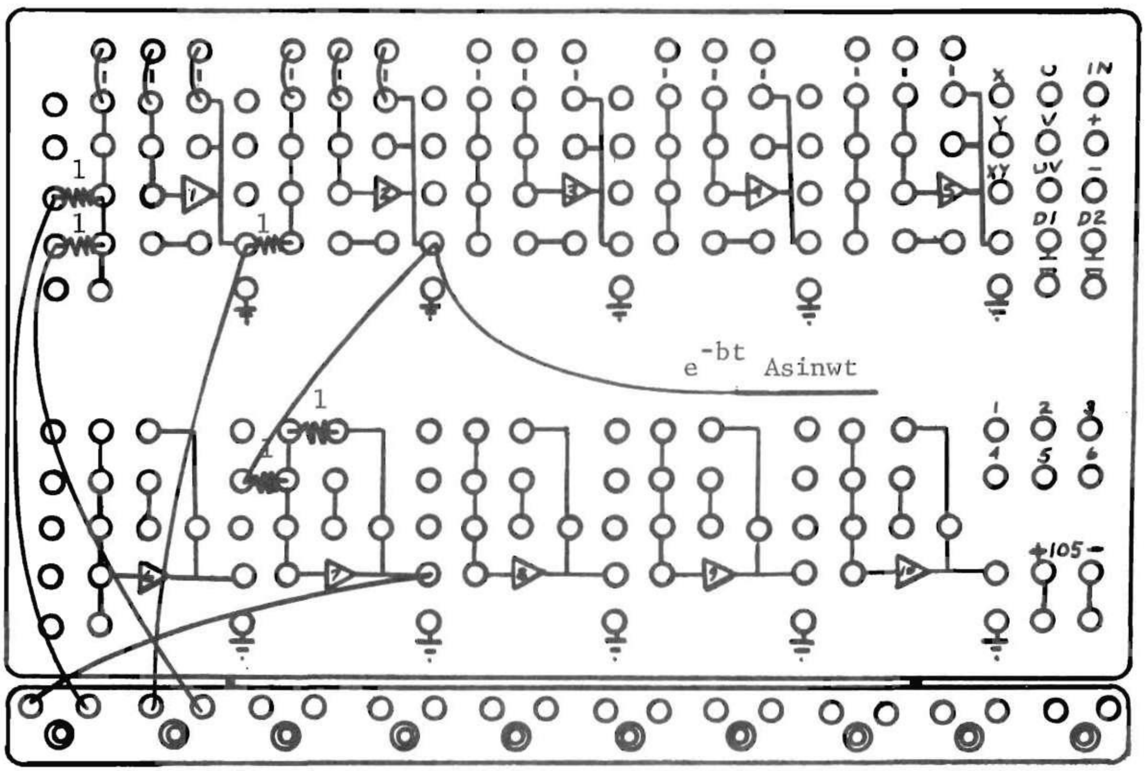
By adding a feedback loop from the output of the first integrator through a potentiometer and into the input of the first integrator, a damped output is achieved. The degree of damping depends on the amplification of the feedback loop. Experience through trial and error is the fastest way of achieving the appropriate damping. If the amplification is great enough, the output signal may be non-oscillatory, yeilding either critical damping or over damping. Figure 16 shows the set up.

Complex

By using any combination of the above function generators in series, complex waveforms may be produced. For instance, using a sine wave function as the input to another sine wave generator (this input is added with the feedback loop or loops at the input of the first integrator) and varying the frequency and/or damping, various signals may be produced.

Determination of Control Order

The control order is easily programmed on the analog computer by using one or more integrators, with the number of integrators used corresponding to the order of control. In other words, if the controller signal is connected in series with two integrators, second order (acceleration) control will be achieved. The positive or negative acceleration in the voltage value out of the second integrator is proportional to the displacement or applied force applied to the displacement or isometric controller, respectively. The rate of



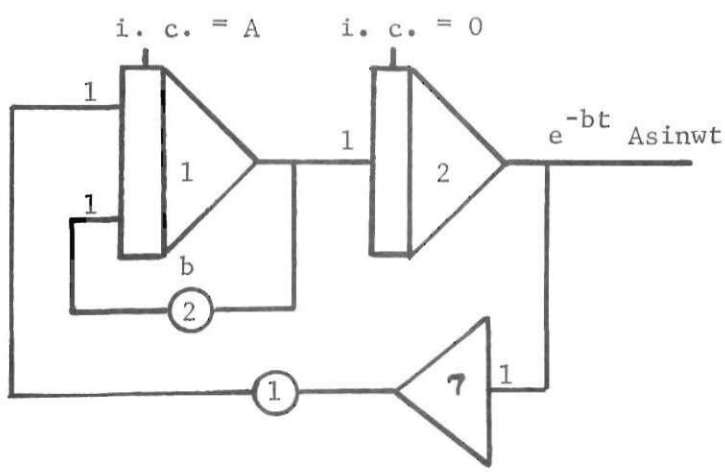


Figure 16. Damped Sine Function Generator Set Up.

change in the voltage value at the output of the first integrator is, similarly, determined by the amount of displacement or amount of applied force. Mathematically, if a constant angle of displacement were set or a constant force was applied, depending on the controller being used, a constant voltage, c, would be the controller output. If we let $f_0(t)$ be the controller output, $f_1(t)$ be the output of the first integrator, and $f_2(t)$ be the output of the second integrator, then

$$f_0(t) = c$$

$$f_1(t) = -\int c\,dt = -ct$$

$$f_2(t) = -\int -\int c\,dt = +\int ct\,dt = 1/2ct^2.$$

In this example the input, c, was a constant. However, the input may be time varying as well, or $f_0(t) = c(t)$. This discussion applies equally well for two dimensional tracking where there are two controller outputs and two pairs of integrators.

Figure 17 illustrates the problem board wiring, or programming, for the case of second order control. Remember that the voltages change sign when passing through an integrator. The control order may be selected or changed at will simply by picking off the voltage at the first integrator output for first order control or at the output of the controller for zero order control. Amplifications other than one may easily be programmed by using the proper input resistors.

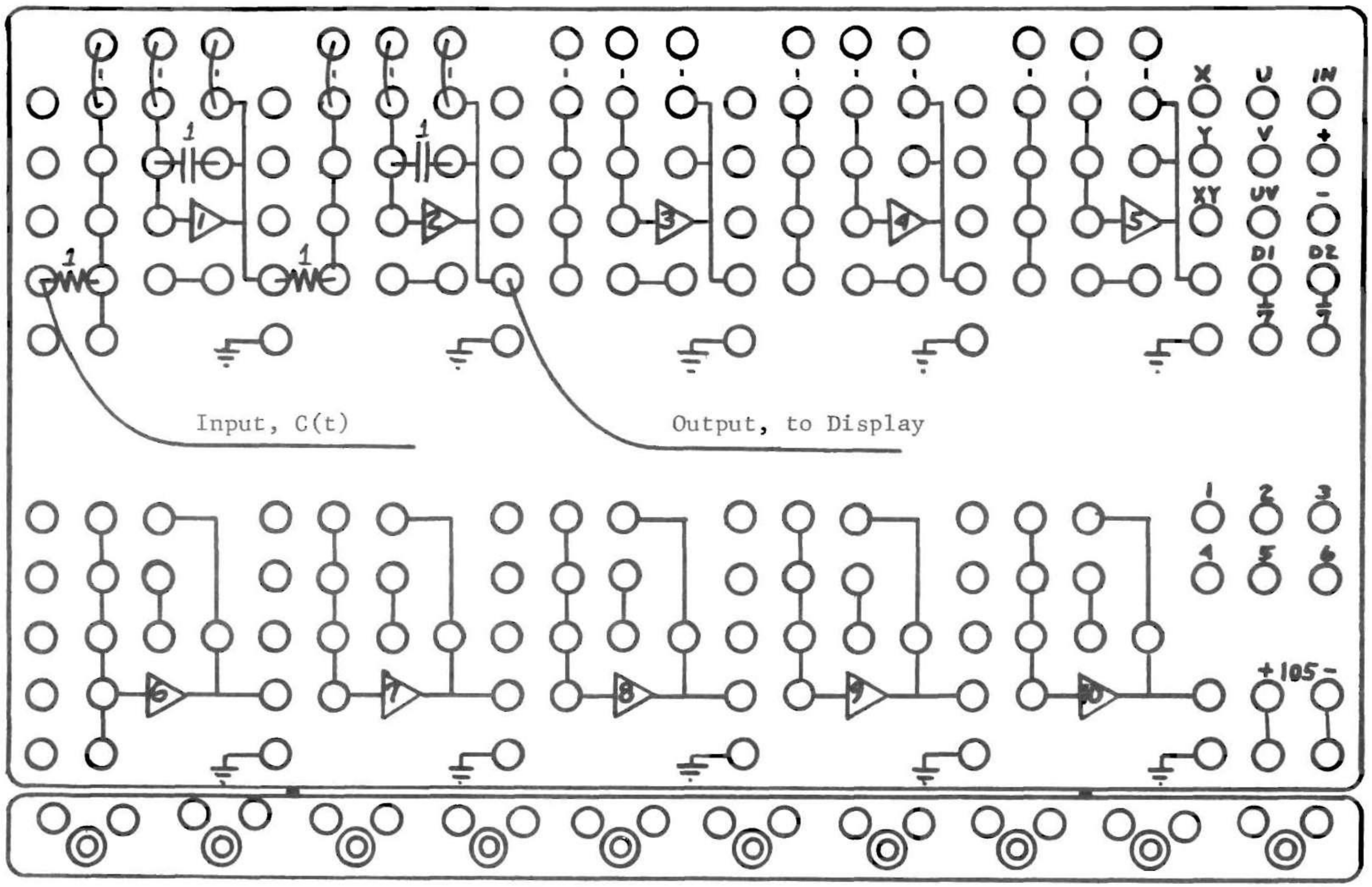


Figure 17. Second Order (Acceleration) Control Set Up.

Aiding

Aiding is a programming exercise consisting of the use of two more amplifiers on the problem board. One amplifier is used to invert the voltage sign of one variable, and the other is used to sum. In the case of first order control, either the output of the integrator or the output of the control (remember that when the output of the control is referenced this means the biased output when using the displacement controller) is inverted, and then both are summed according to the proper ratio. For an aiding ratio of 1:2 (which corresponds to an aiding constant of .5 sec.), the input resistors are selected such that output from the integrator is amplified twice as much as the output from the controller. In other words, the signal displayed, f(x), is related to the controller action, x, according to the function

$$f(x) = kx + (2k) \quad xdt.$$

Higher order aiding is a matter of adding more terms to the above equation. Figure 18 shows an aiding set up.

Error Measurement

The analog computer components used in the error measurement portion of the system are the most sensitive to adjustment and non-linearities. Some practice and testing on the set up used should be made to arrive at the proper amplifications and voltage ranges. It is important to realize that the analog computer has a voltage range of ± 100 volts. The more of this range that can be used, the less significant the fluctuations and other uncontrollable errors will be.

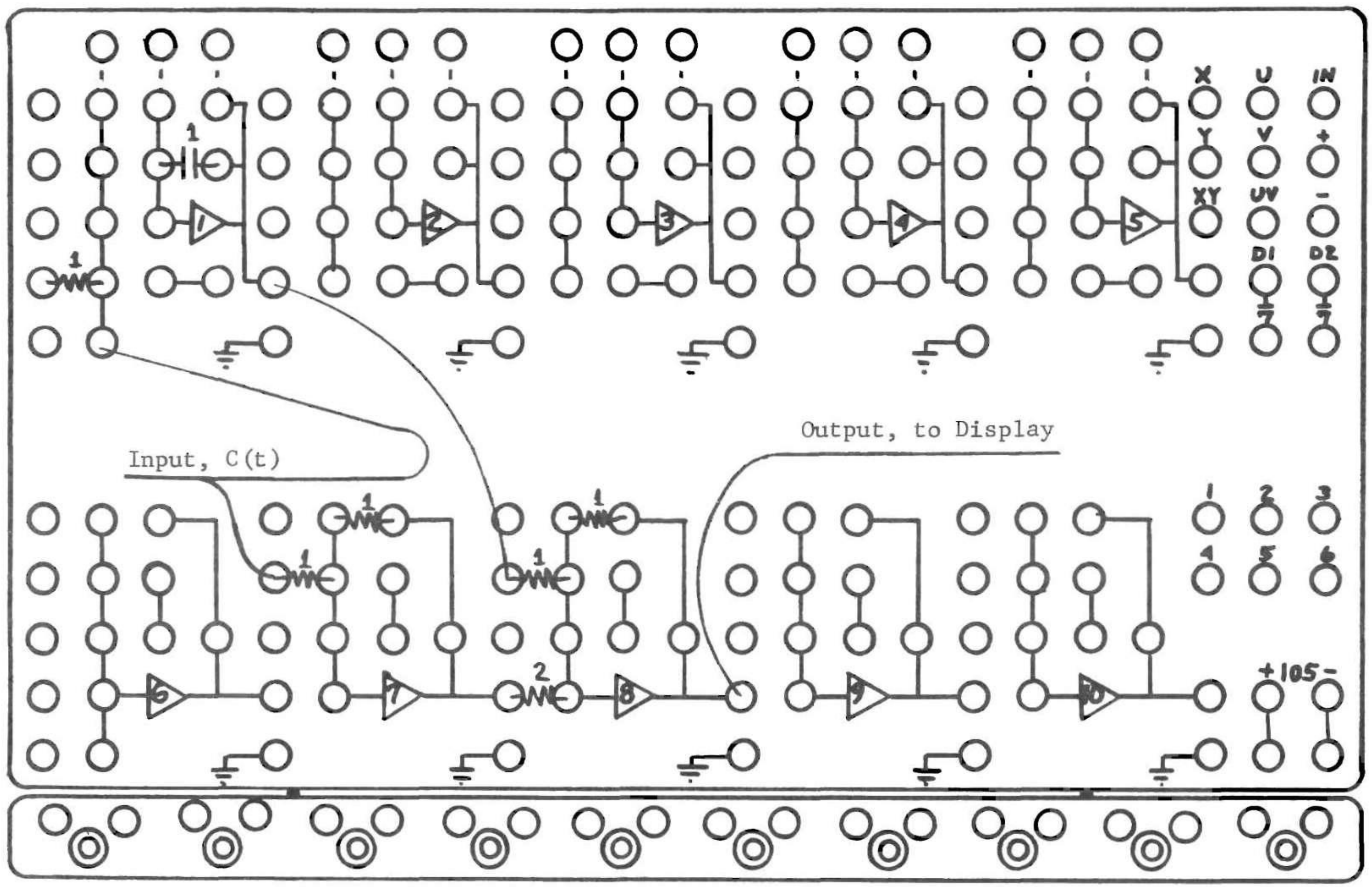


Figure 18. First Order (Velocity) Control with Aiding Set Up.

One Dimensional Tracking

The circuits for this form of tracking error measurement are considerably simpler, more accurate, and more reliable than the circuits required for two dimensional tracking. The chief reason is that a square root device is not necessary.[7] Figures 19, 20, and 21 illustrate the wiring of the mean of error, mean value of error, and mean square error performance criteria circuits. Time on target is arrived at by a direct plot of e(t), and the amount of time e(t) exceeds the set control limits is determined by inspection.

Two Dimensional Tracking

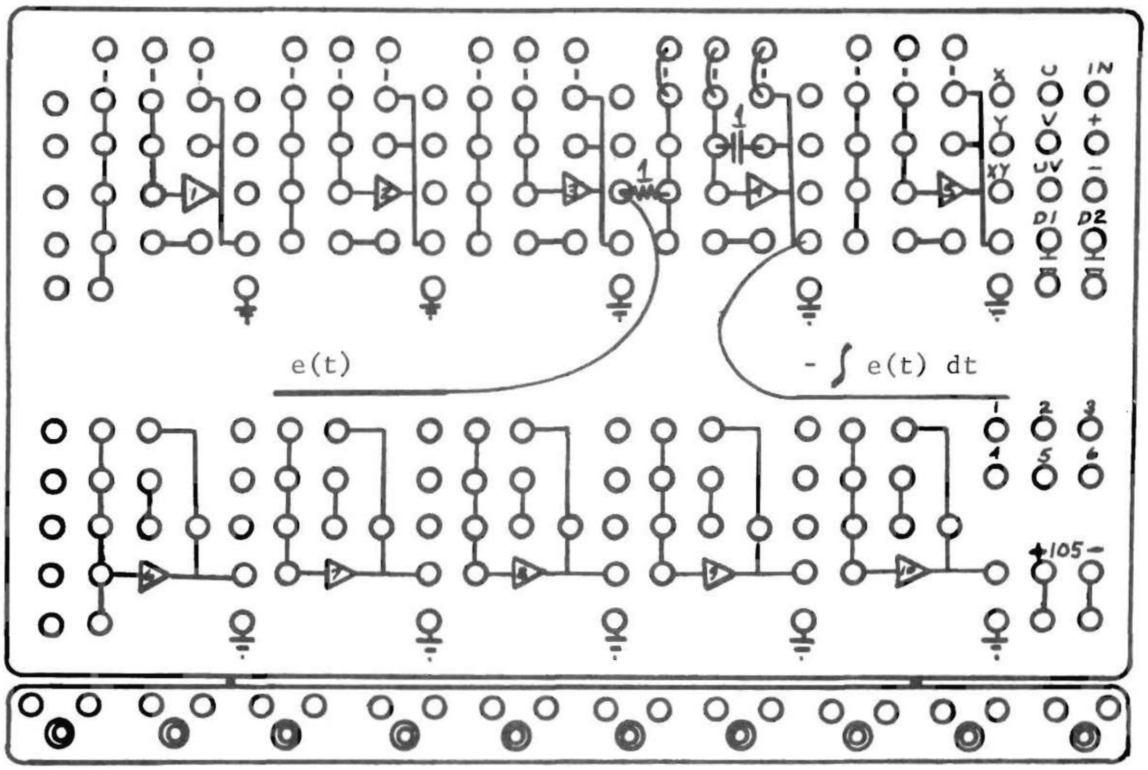
As was mentioned, the circuits for measuring the error in two dimensional tracking are a bit more involved than with one dimensional tracking. Now, e'(t) is just the magnitude defined as

$$e'(t) = \sqrt{e_x^2(t) + e_y^2(t)}.$$

The diode circuit for obtaining absolute values cannot be used. The x and y components of error must be squared, summed, and the square root of this sum of squares taken.

Mean of Error. Using e'(t) as defined above would not yield enough information about the mean of the error, since e'(t) is only a

7. The operation of the function multiplier and square root device on the analog computer is a fairly involved procedure to explain here. The reader is referred to the manufacturer's instructions.



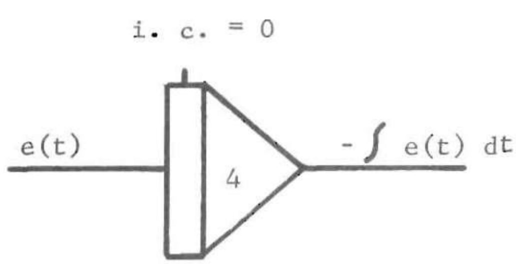


Figure 19. Average Error, One Dimensional Tracking Set Up.

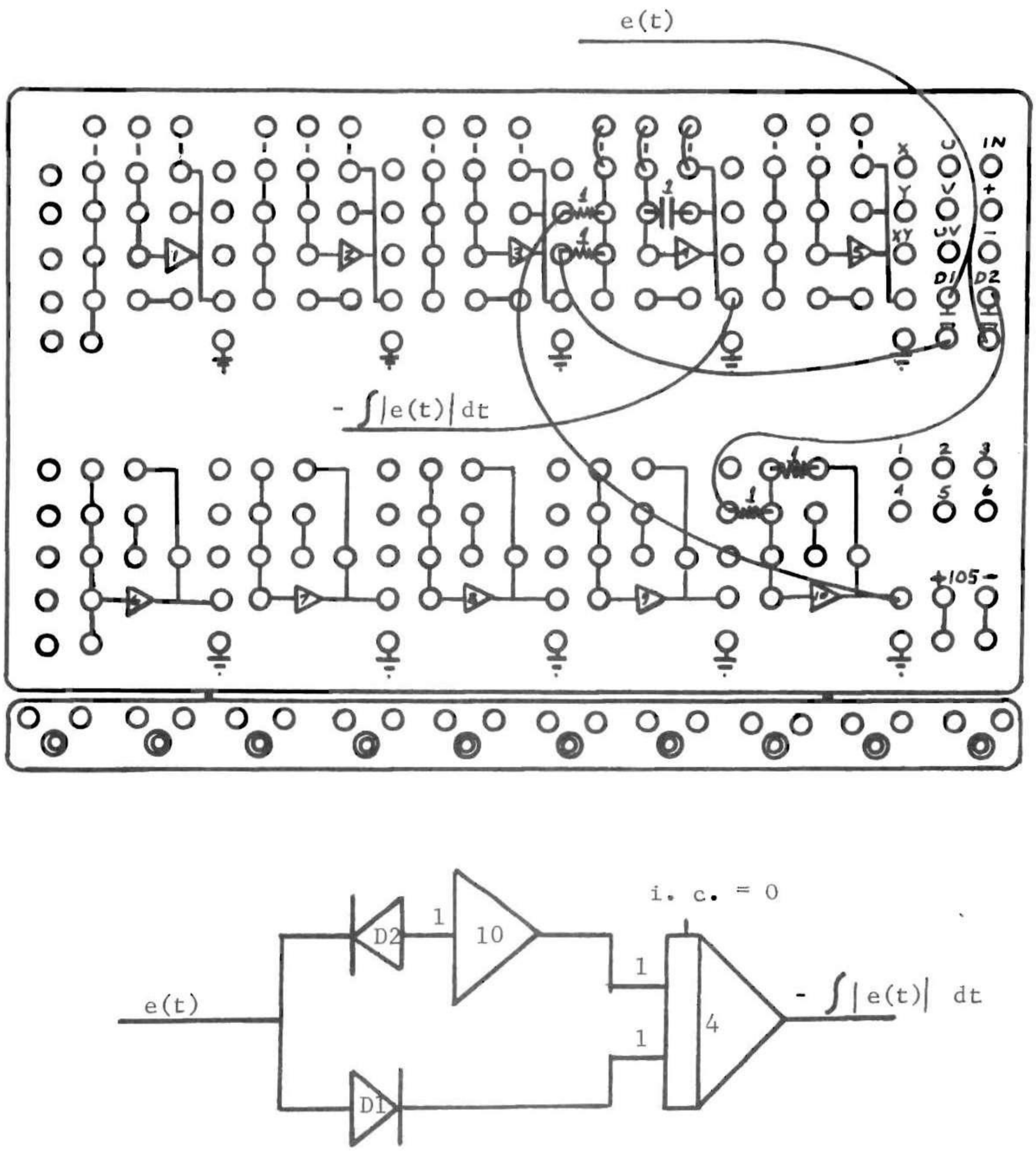
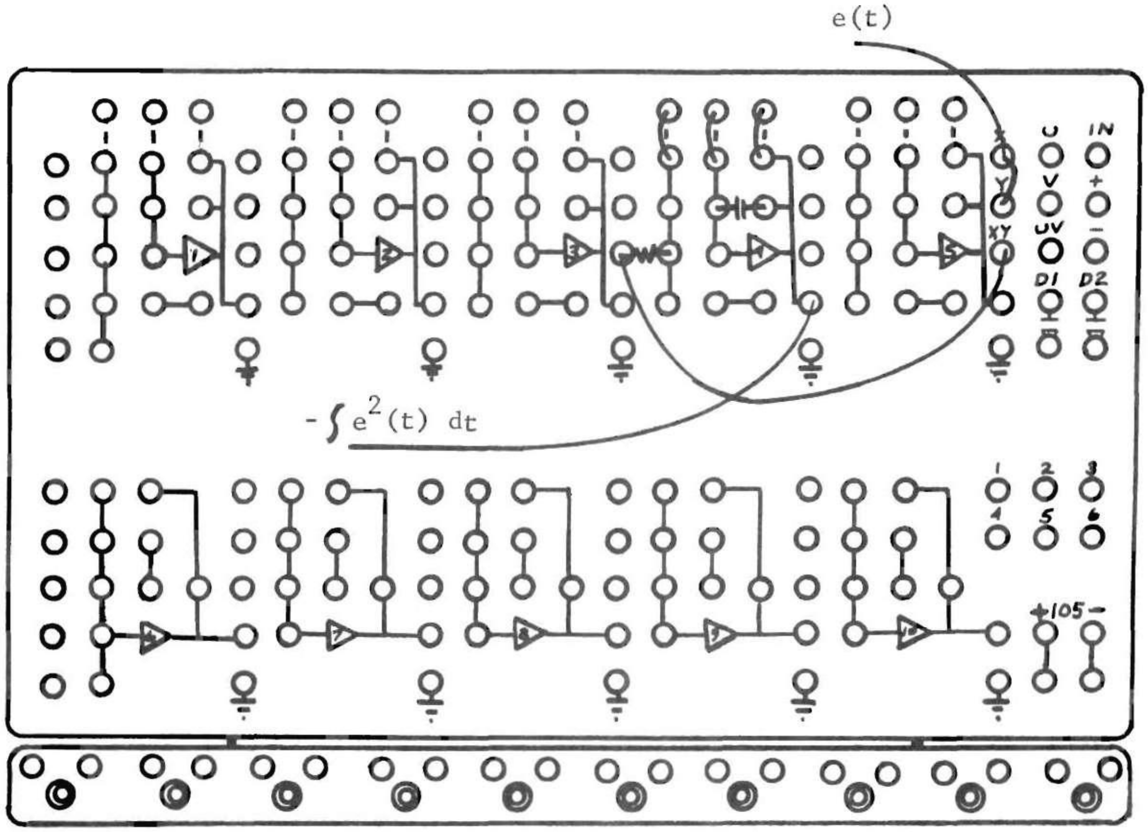


Figure 20. Mean Value of Error (Root Mean Square), One Dimensional Tracking Set Up.



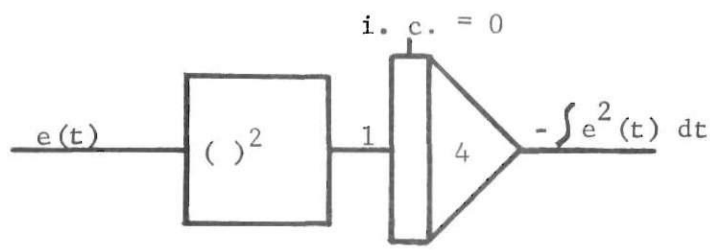


Figure 21. Mean Square Error, One Dimensional Tracking Set Up.

magnitude, and no knowledge of the direction of the error may be gained. The procedure here must be to get separate measurements of the x and y components of the mean of error. Then the experimenter may plot these on graph paper to find both the direction and magnitude of the mean of error. Figure 22 illustrates the wiring circuit for this performance measurement set up.

Mean Value of Error. Only a magnitude is required for this criterion, thus the mean value of error may be found by an integration of $e'(t)$. See Figure 23 a. and b.

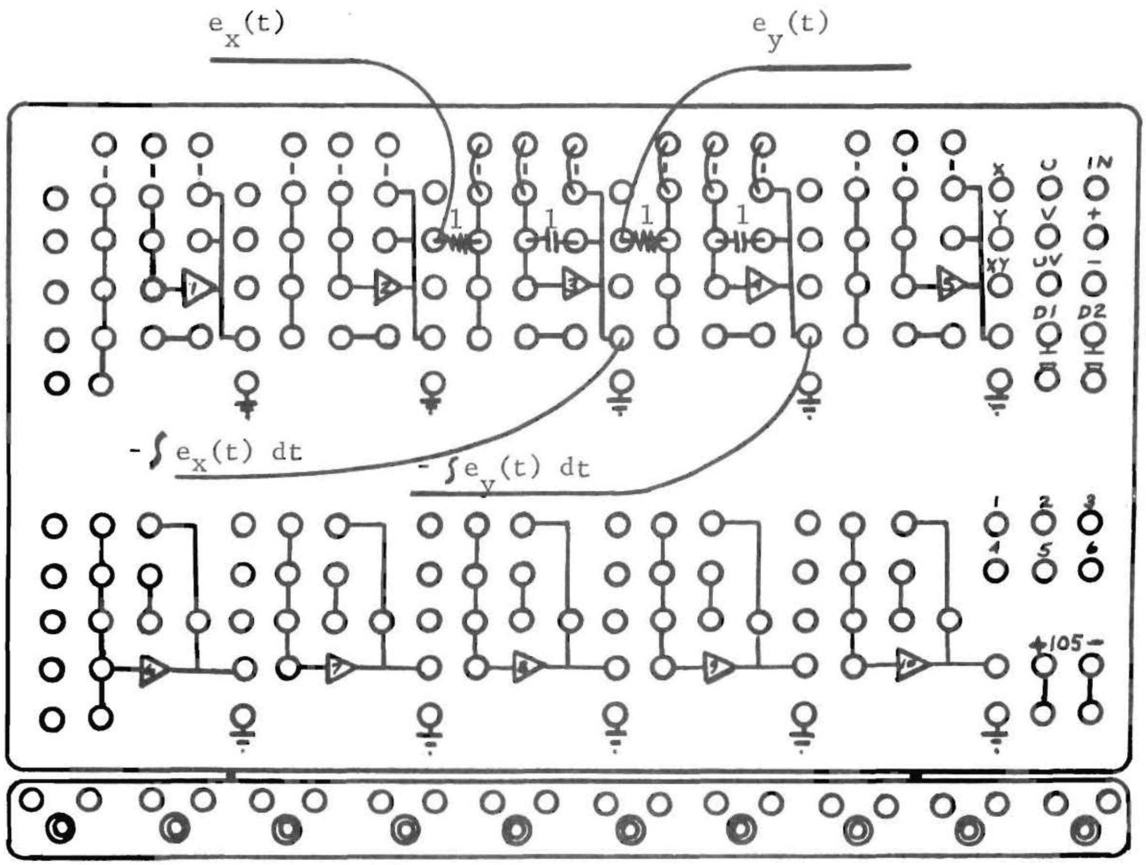
Mean Square Error. This is determined simply by taking the sum of square, or $e'^2(t)$, and integrating it. See Figure 24.

Time on Target. The explanation is the same as for one dimensional tracking, except $e'(t)$ is used instead of $e(t)$.

Operation, Checkout, and Calibration Procedure

The following steps are suggested as a systematic procedure for running an experiment on the tracking system:

1. Using the list of System Variables in Chapter II, determine the kind of tracking set up desired.
2. Draw a schematic of the desired computer set up. (Figure 25 is an example of such a schematic.) In this set up keep track of the voltage scaling. The final output may easily be some multiple of the statistic which is desired, and only by keeping the amplifications of the summers, integrators, and other devices straight can this output be correctly interpreted. The squarer and square root devices used together produce an



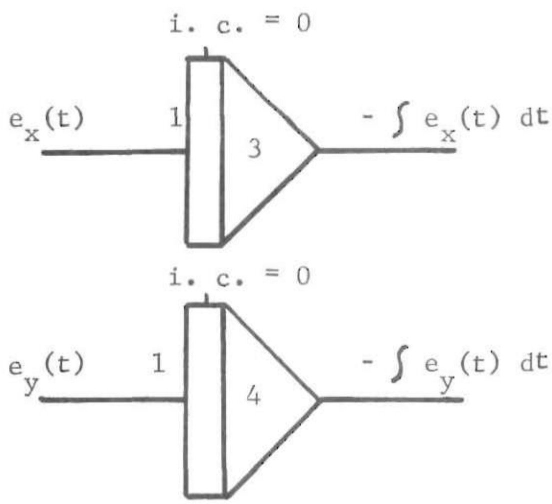


Figure 22. Average Error, Two Dimensional Tracking Set Up.

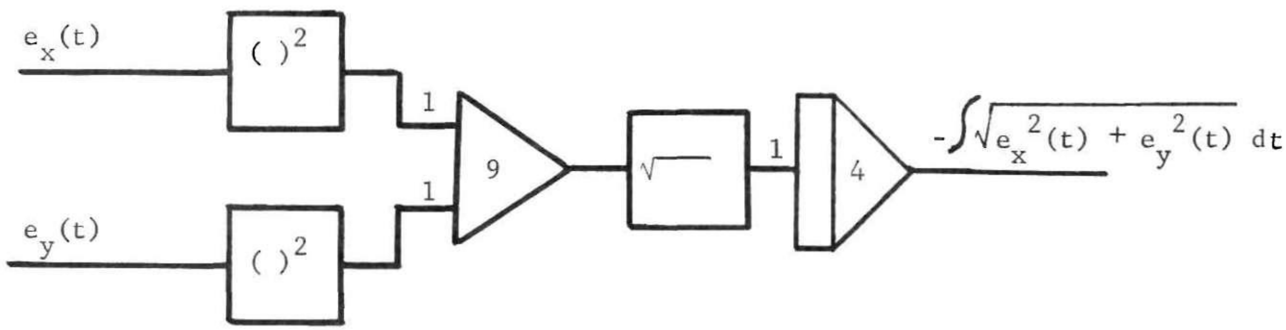


Figure 23a. Mean Value of Error (Root Mean Square), Two Dimension Tracking Set Up.

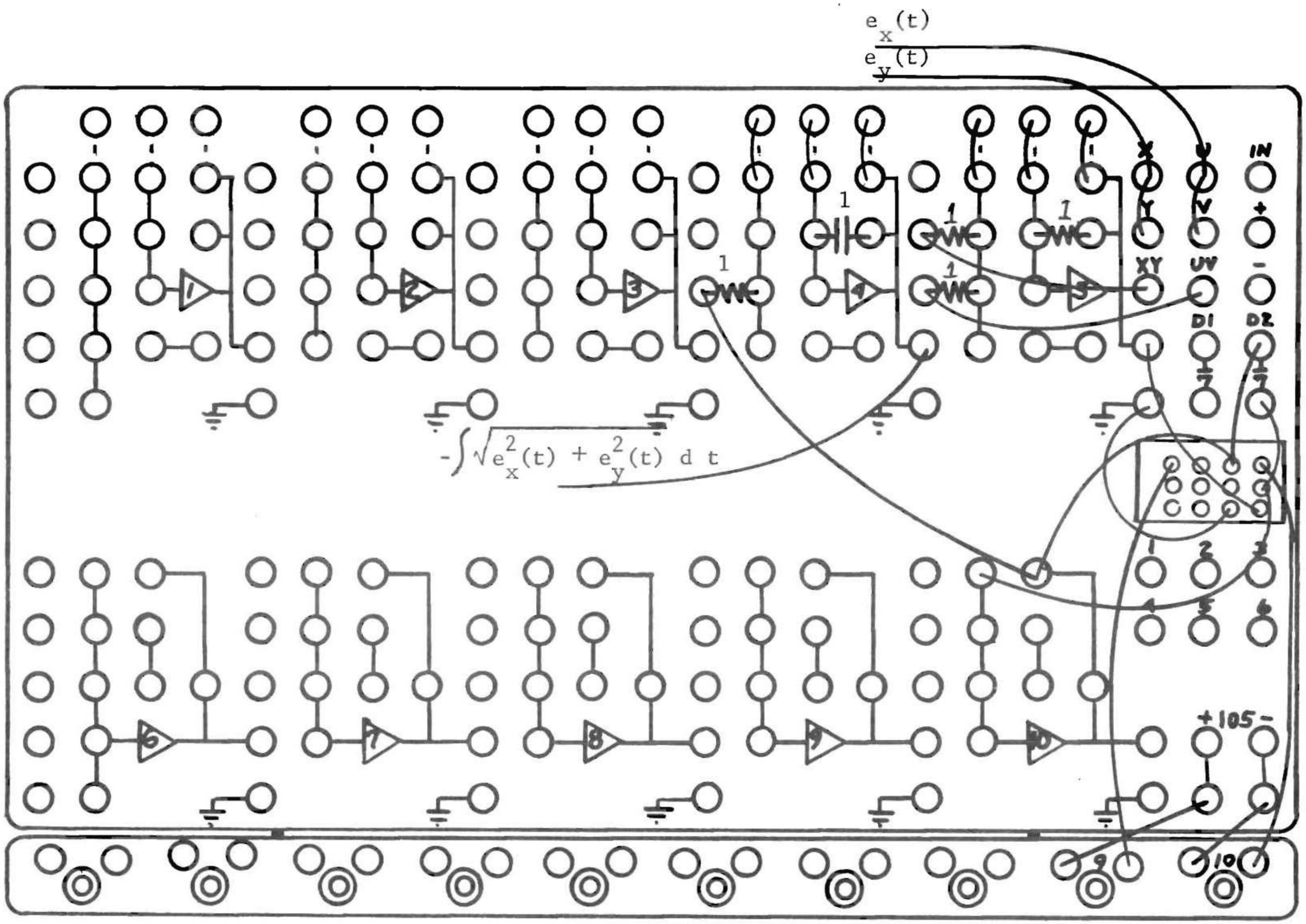


Figure 23b. Mean Value of Error (Root Mean Square), Two Dimensional Tracking Set Up.

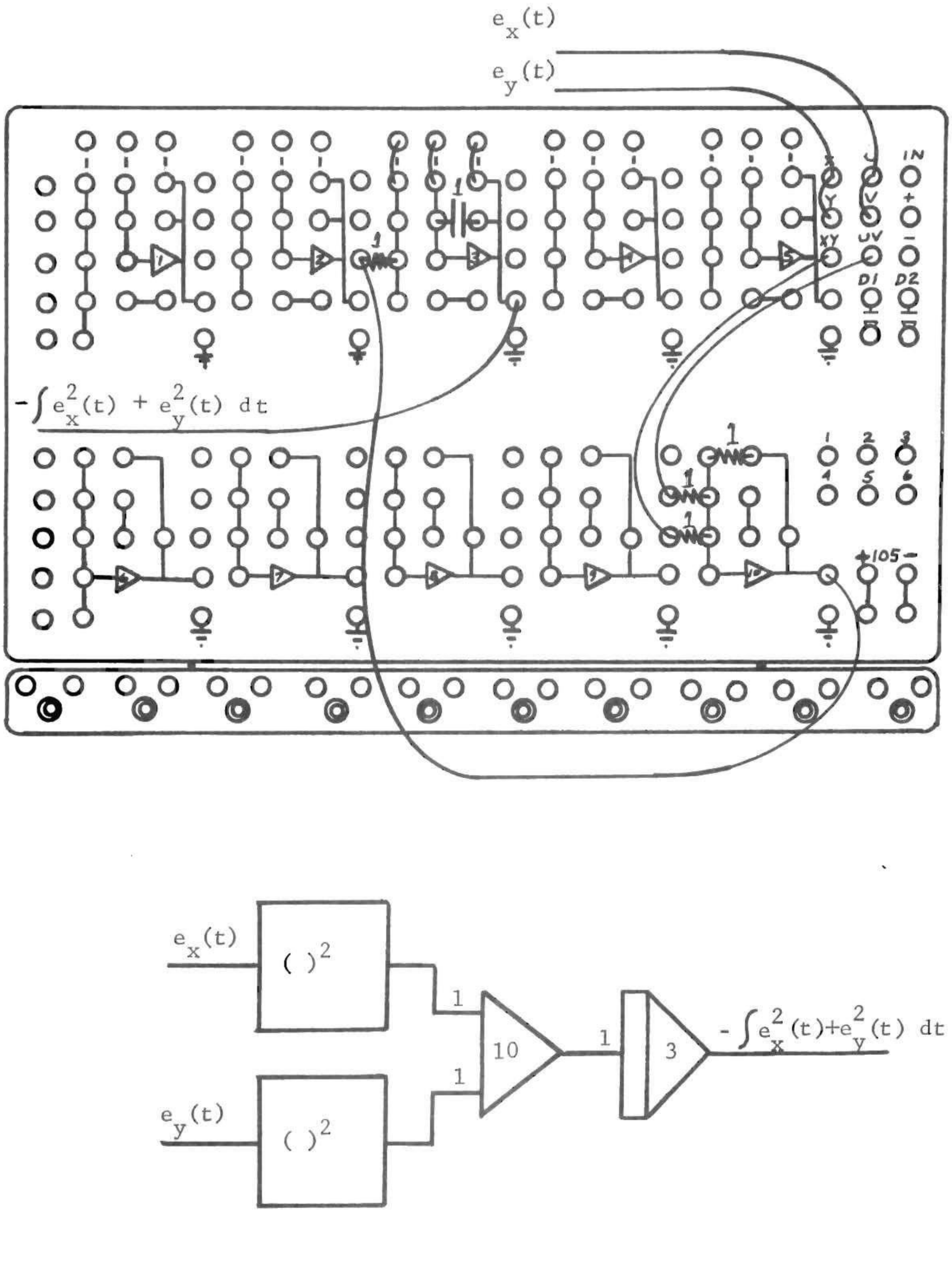


Figure 24. Mean Square Error, Two Dimensional Tracking Set Up.

error for inputs under 10 volts (see Appendix III). The input, then, should be scaled so that it uses as much of the 100 volt range as possible. In other words, minimize the use of the 0-10 volt input range as much as possible.

3. (Optional) Draw the set up on a diagram of the problem board. (Appendix II contains two blank diagrams which may be used to make reproductions. In this way a copy of the blank diagram can always be obtained.)
4. Wire the set up on the problem board of the analog computer.
5. Check output voltage of hand controller and adjust the bias while the joystick is in a zeroed state until this output voltage is zero.
6. Adjust the inputs to the error, e(t), on the computer so that it is zero. Then, for pursuit display, adjust the "POSITION" knob on the electronic switch(es) until coincidence of the cursor and the target is achieved. In the case of compensatory display simply adjust the horizontal and vertical positioning of the oscilloscope beam (on the oscilloscope) to the desired zero reference position.
7. To check out and calibrate the equipment, (1) adjust the voltage of e(t) to be the maximum amount possible (say 80 volts). For Pursuit Display Only - This may be done by: first, setting up the experiment without attention to the performance measurement. Once the display is adjusted and calibrated, a proper amplification of e(t) may be selected to obtain this maximum output. For Compensatory Display Only -

(Ignore the previous discussion on pursuit display.) Then adjust the maximum error displayed to the desired amount through the gain settings on the oscilloscope.

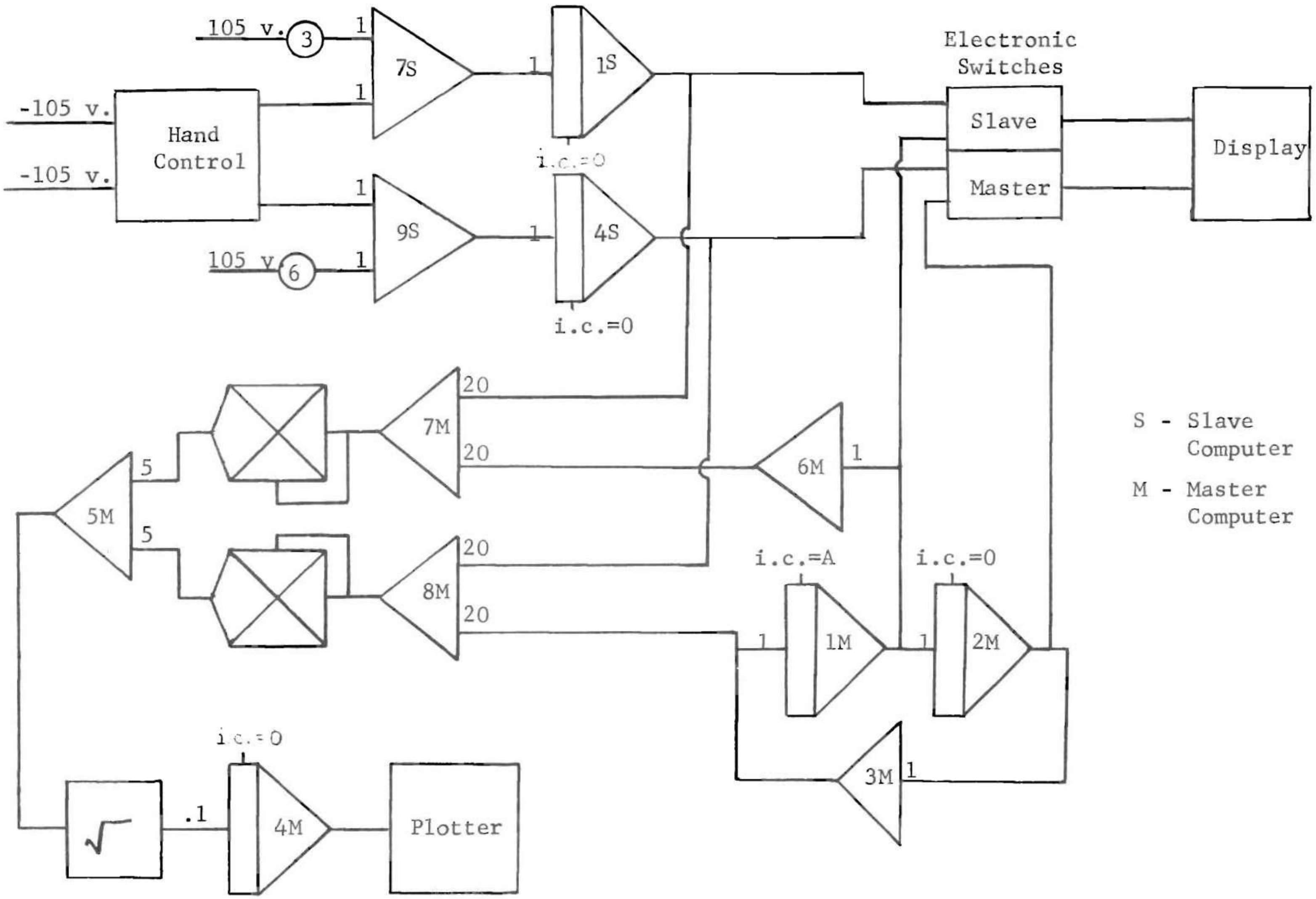
(2) With this value of e(t), turn on the computer and plotter, and make a trial run. Calibration may be checked with this reference test input.

8. Keep in mind that this system is flexible enough so that any systematic errors that crop up can be eliminated, using careful checkout and calibration.

Example

Figure 25 gives an example of a displacement controller, first order, non-aided, pursuit tracking situation with mean value of error criteria being recorded and the cursor being driven by a sine wave generator utilized to produce either a circle or an ellipse.

After some experience, a particular set up arrangement has been found to be very acceptable with the two analog computers used in this tracking system. Figures 26 and 27 show the tracking system as it is set up to perform this example. The left hand computer problem board, in Figure 27, is used to simulate the machine. The left half of the problem board for one dimension and the right half for the other dimension. The analog computer on the right (master) performs the functions of generating the input signal (upper left), calculating the performance error (right), and adjusting the electronic switch output for the oscilloscope (lower center).



S - Slave Computer

M - Master Computer

Figure 25. Schematic of Example Set Up.

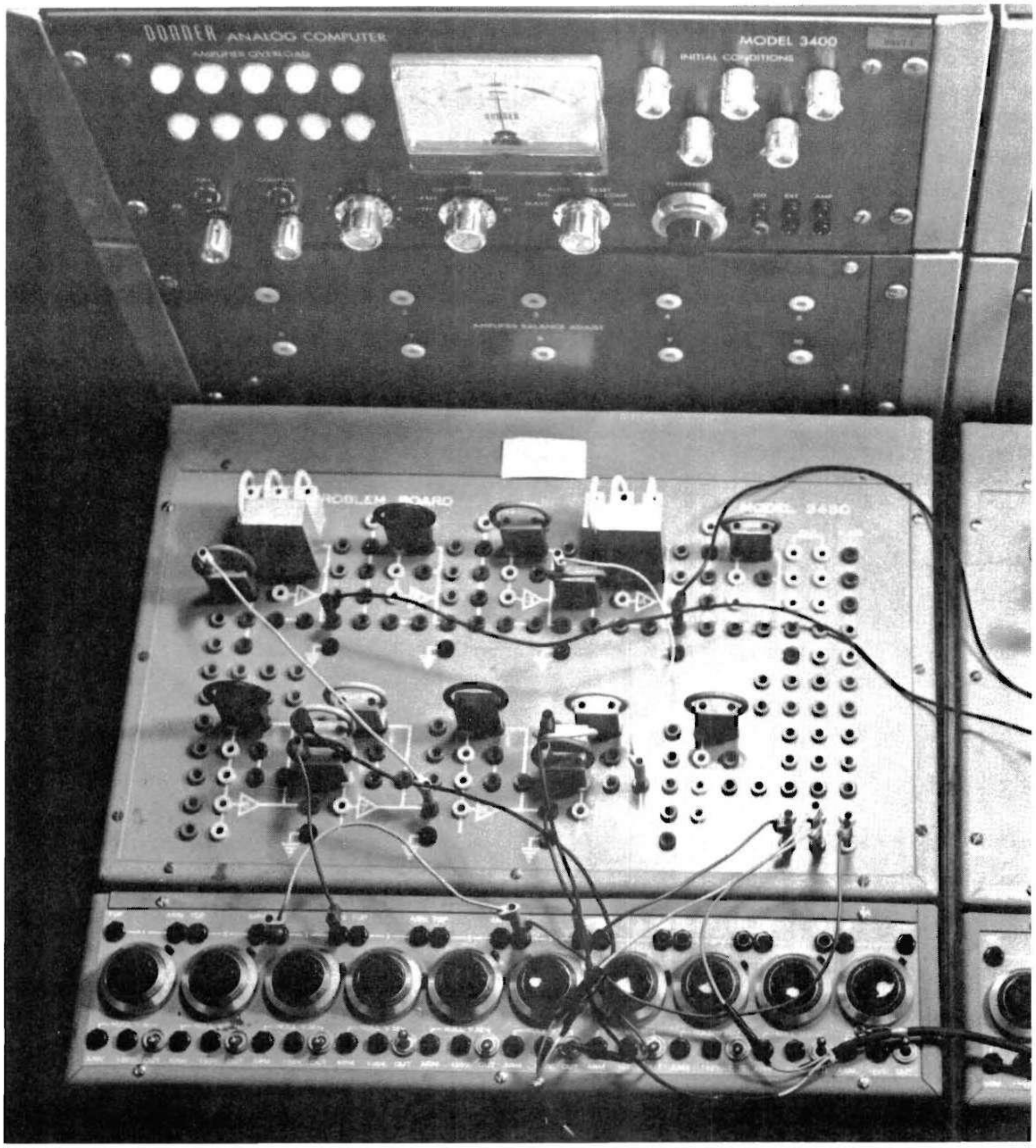


Figure 26. Problem Board of the Slaved (S) Analog Computer for the Example Problem.

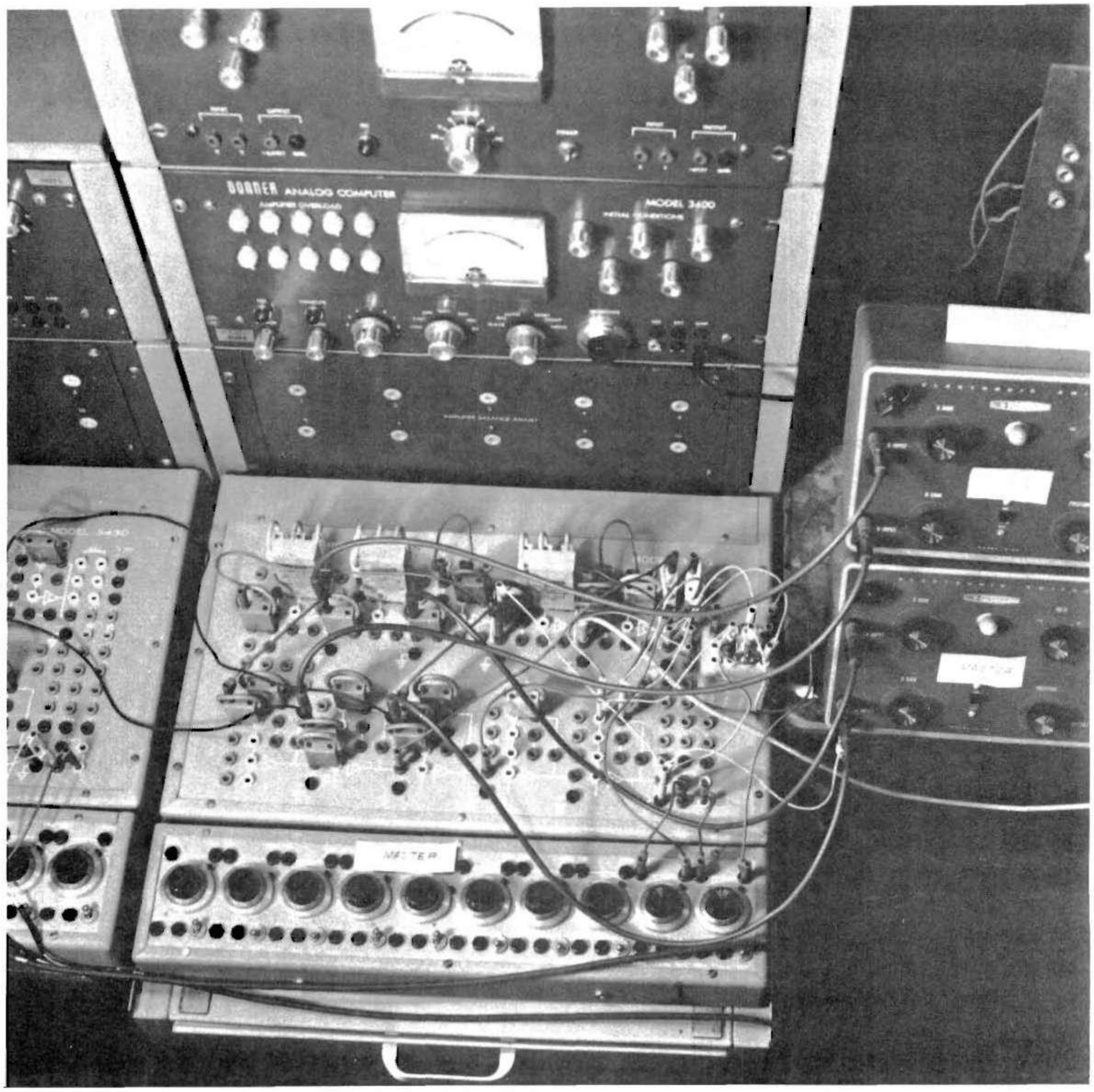


Figure 27. Problem Board of the Master (M) Analog Computer for the Example Problem.

CHAPTER IV

RECOMMENDATIONS FOR FURTHER EXPANSION

An Input Function Generator Alternative

Since there are two hand controllers it is quite feasible to use one of the controllers to act as an input function to the cursor. This set up would enable the use of complex signals not producable on the analog computer. The controller may hook directly to the target, or the controller may serve as an input to some simulated system programmed on the problem board. The possibilities are practically unlimited, and some imagination would result in rather interesting tasks.

Intermittent Displays

All the tracking tasks alluded to in this thesis are of a continuous nature. Discrete, or intermittent, tracking tasks could be performed by controlling the z-axis, or brightness, of the oscilloscope display.

Other Displays

The oscilloscope display is only one type of visual display which could be used with this tracking system. Dials, pointers, and meters are all possibilities for a display in addition to the oscilloscope. For instance, compensatory tracking could be accomplished by using the analog computer panel meter to register the voltage of e(t).

Other Type Sensory Input and Output

Only one type input, visual, and one type output, manual, was utilized in the design of this tracking system. If, for example, the FM tape recorder was hooked into the system, auditory tracking could be employed by broadcasting the signal which was converted to frequencies over a speaker. In this system the operator's task would be to match one frequency, corresponding to the desired machine state, with another frequency, corresponding to the machine state which he is controlling.

Transport Delays

There exists within the capability of the particular analog computer being used in this sytem a component which can induce time lag delays. The shape of the signal is not distorted in any way. An example of how this device could be used would be to induce a time lag after the controller. This would be like the situation of controlling a TV camera on the moon and trying to track the Lunar Excursion Module as it blasted off. Possibly other uses could be implemented with some imaginative investigation.

Present, Alternate, and Supplemental Equipment for the System

Table 1 lists (1) the equipment used in the tracking system described in this thesis along with the money which was spent for those items and (2) equipment which could be bought and put together to perform the same functions as the present system.

In addition, there are several pieces of equipment which could supplement or be a replacement component for either system. It is not

Table 1. Cost of Present Tracking System and Price for a New Tracking System Which Would Perform the Same Functions.

Requirement	Present Equipment	Cost	New Equipment	Cost
Display	Allan B. Dumont Laboratories, Inc. Model 304H Oscilloscope	-0-	Heathkit Model IOW-18 Oscilloscope	$ 164.95
	Heathkit Model ID-18 Electronic Switch (2 needed)	30.95		
Hand Controllers	Measurement Systems, Inc. Model 433 and Model 525 Hand Controllers	-0-	Same	1,500.00 130.00
Power Supply	Digital Equipment Corp. Model 721 Power Supply Lambda Corp. Model LT-1095M Power Supply	-0-	Heathkit Model IP-18 Power Supply (2 needed)	25.95 25.95
Function Generator Machine Simulation Performance Measurement	Systron-Donner Co., Inc. Model 3400 Analog Computer	-0-	Systron-Donner Co. Model SD 20 Analog Computer (contains an electronic switch capability)	13,000.00[8]
Plotter	Houston Onmigraphic Co., Inc. Model HR-97 X-Y Plotter	-0-	Hewlett-Packard Co., Inc. Model 7004 X-Y Plotter	1,395.00
		$61.90		$16,241.75

8. Price depends a great deal on the options selected. This price given is an estimated cost which would cover the options needed to satisfy the minimum requirements.

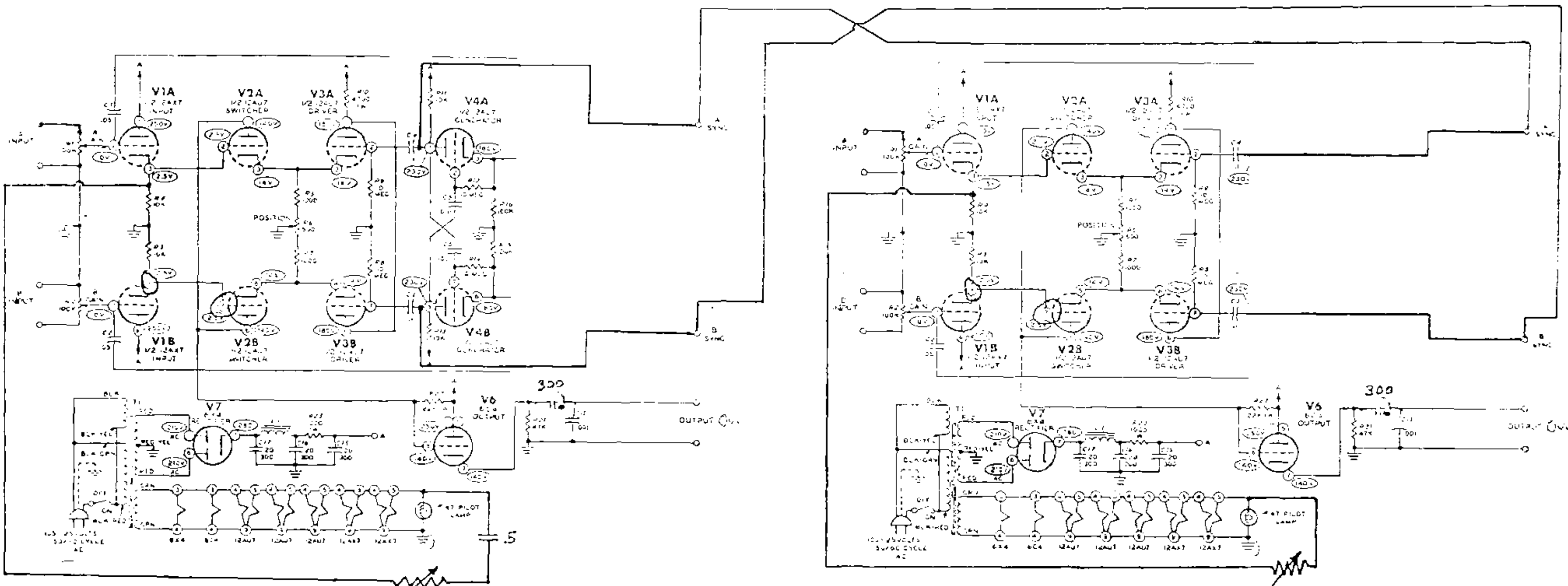
necessary to have these items, but the capabilities of the tracking system would be greatly enhanced by their additions. First, the Tecktronix Oscilloscope Model 561B with two Model 3A72 Plug-In Units could replace the more inexpensive oscilloscopes used for the display. The primary advantage of this oscilloscope is that it does not require external electronic switches to time-share the beam. Second, a Hewlett-Packard Analog Tape Recorder would be useful to (1) record and play back the results of an experiment for analysis under more than one of the performance criteria, (2) record complex functions for use as the target input during an experiment, and (3) to permanently record a tracking experiment for later playback as a demonstration. Third, a Hewlett-Packard Model 3310A Signal Generator could be used for generating sine, triangle, saw tooth, square, ramp, and step functions. A signal generator such as this one would (1) facilitate varying the input signal in the tracking system, (2) provide a wide range of different wave forms, (3) and provide a sweep for the target signal at frequencies lower than those capable for the oscilloscope being used. This sweeping would be possible through use of the saw tooth function as an input to the horizontal component of the target. Table 2 lists these three items and their price.

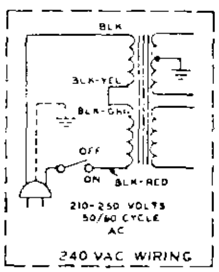
Table 2. Prices of Supplemental Equipment

Item	Cost
Tectronix Model 561B Oscilloscope with Two Model 3A72 Plug-In Units	$1,595.00
Hewlett-Packard Model 3690 Analog Tape Recorder (4 Channels)	4,285.00
Hewlett-Packard Model 3310A Signal Generator	575.00

APPENDIX I

Schematic of the Electronic Switches



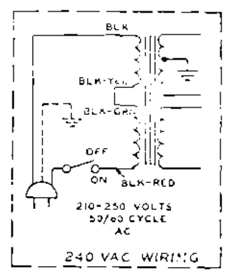


NOTES:

1. ALL RESISTOR VALUES IN OHMS, K = 1,000, MEG = 1,000,000.
2. ALL CAPACITOR VALUES IN μfd.
3. ALL VOLTAGES MEASURED FROM POINT INDICATED TO CHASSIS GROUND WITH A VTVM. VOLTAGES MAY VARY ±20%.

SCHEMATIC OF THE HEATHKIT® ELECTRONIC SWITCH MODEL ID-22

MASTER



NOTES:

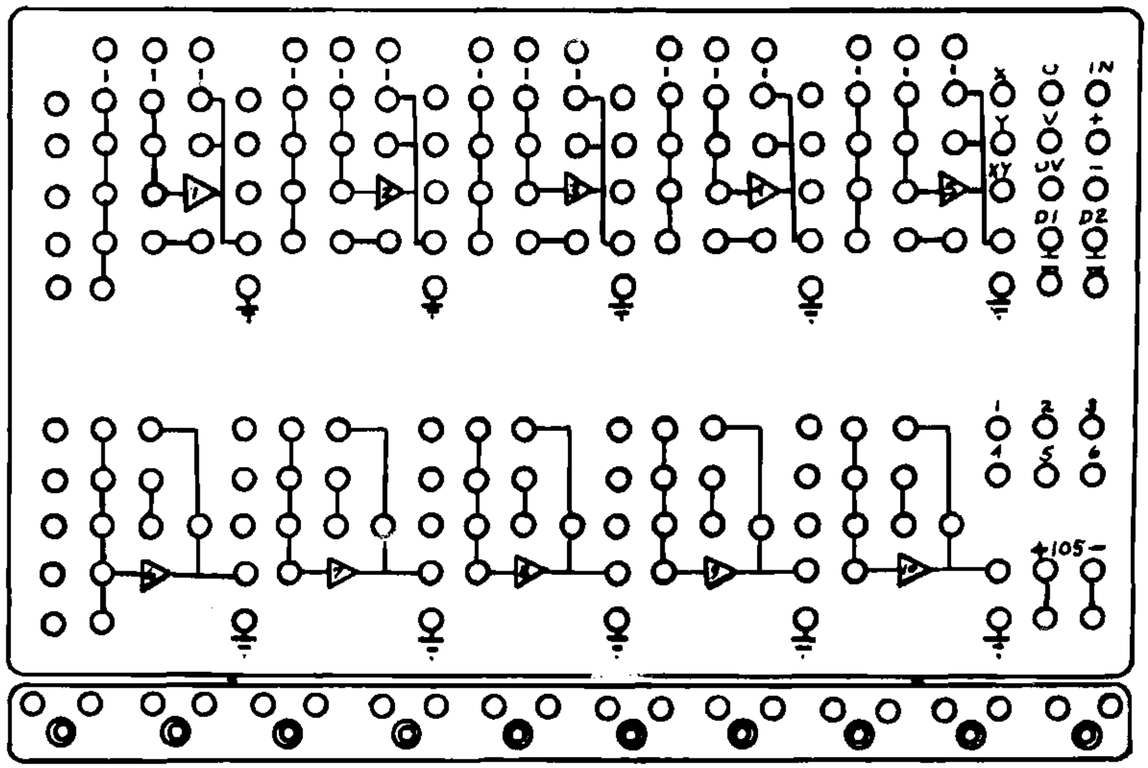
1. ALL RESISTOR VALUES IN OHMS, K = 1,000, MEG = 1,000,000.
2. ALL CAPACITOR VALUES IN μfd.
3. ALL VOLTAGES MEASURED FROM POINT INDICATED TO CHASSIS GROUND WITH A VTVM. VOLTAGES MAY VARY ±20%.

SCHEMATIC OF THE HEATHKIT® ELECTRONIC SWITCH MODEL ID-22

SLAVE

APPENDIX II

Blank Analog Computer Problem Board Diagrams


X
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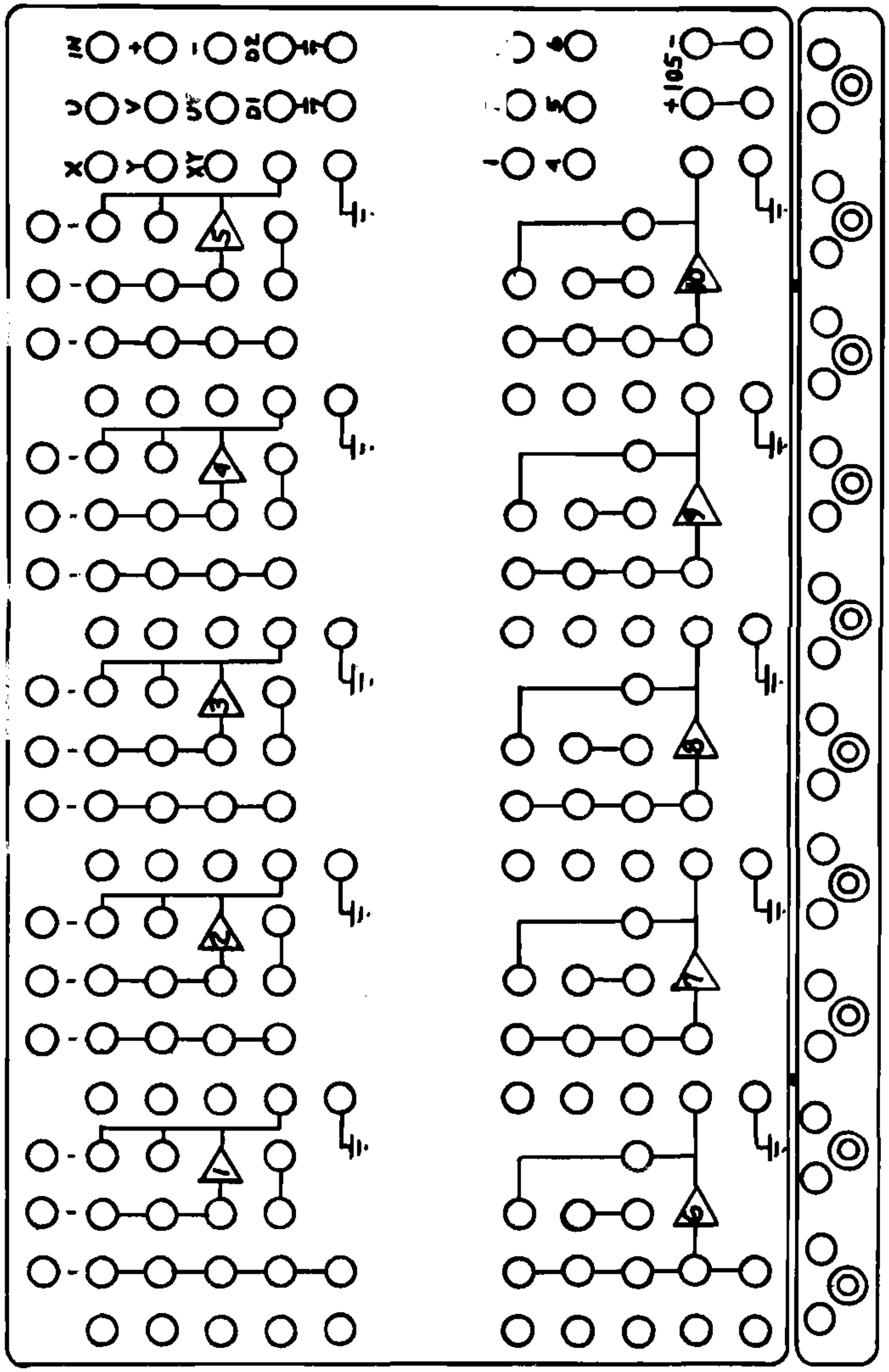


APPENDIX III

Input-Output Plots of the Square and Square Root Devices on the Analog Computer

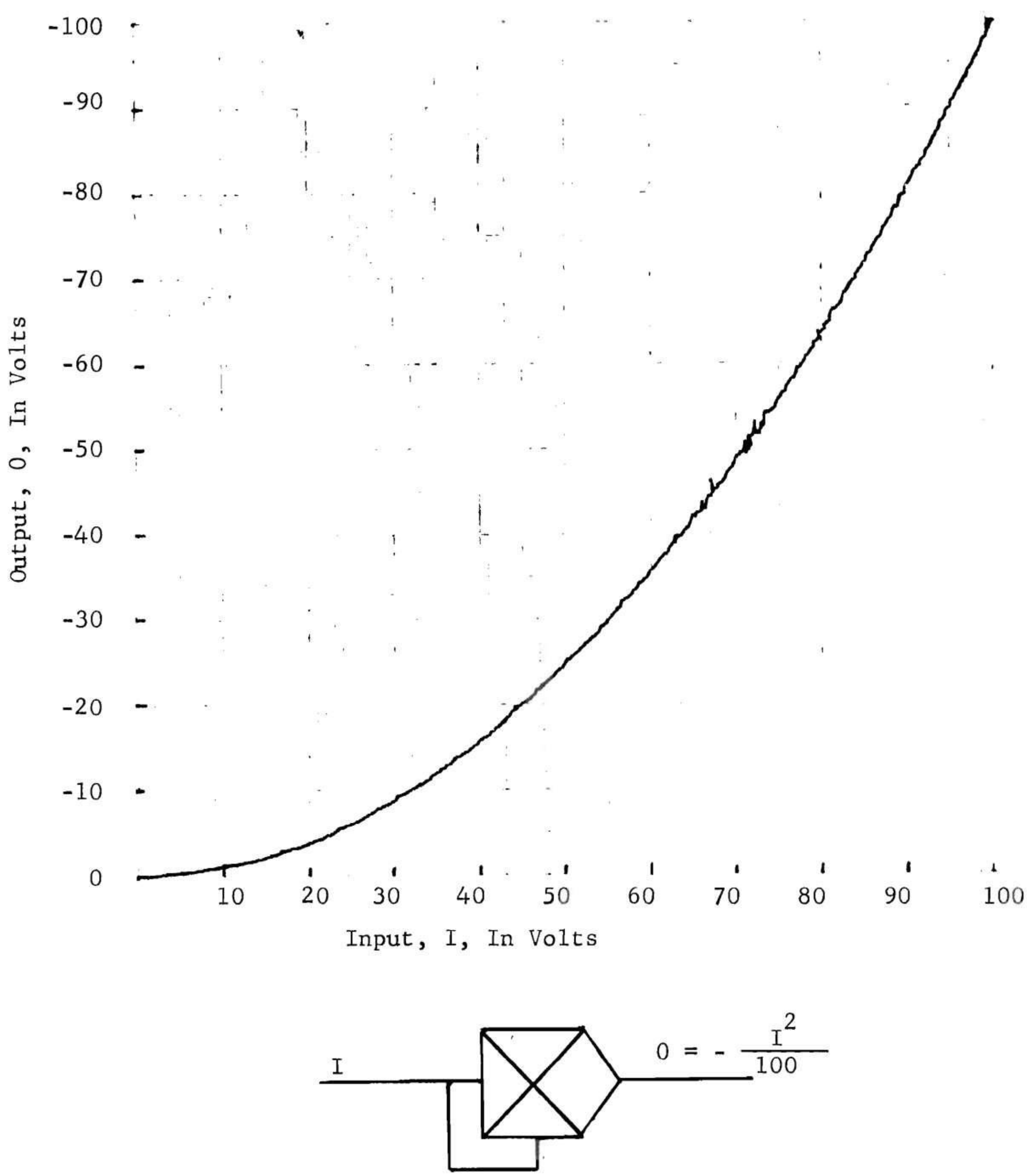
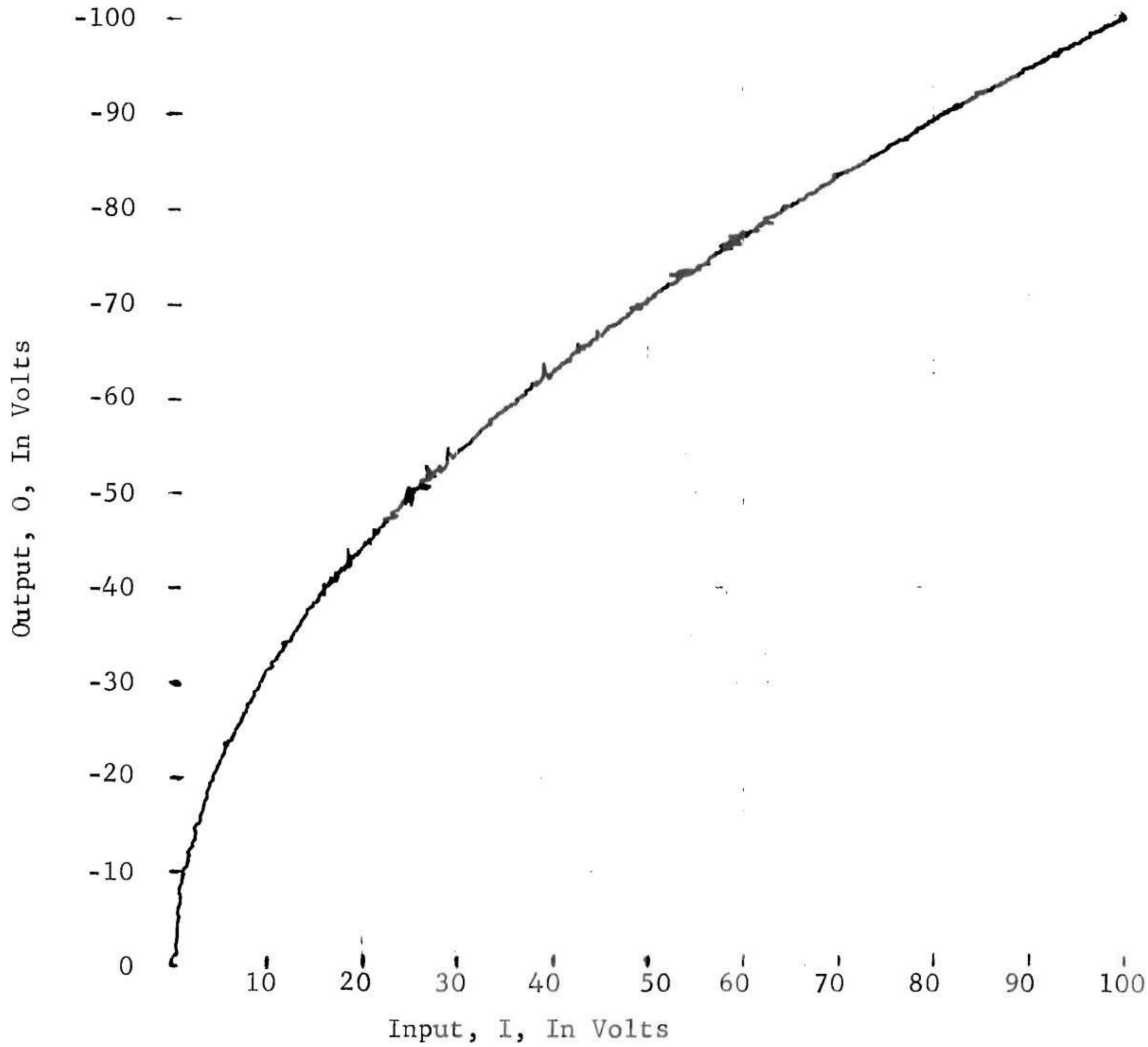


Figure 28. Input-Output Plot of the Squarer Device.



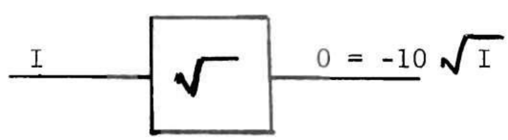


Figure 29. Input-Output Plot of the Square Root Device.

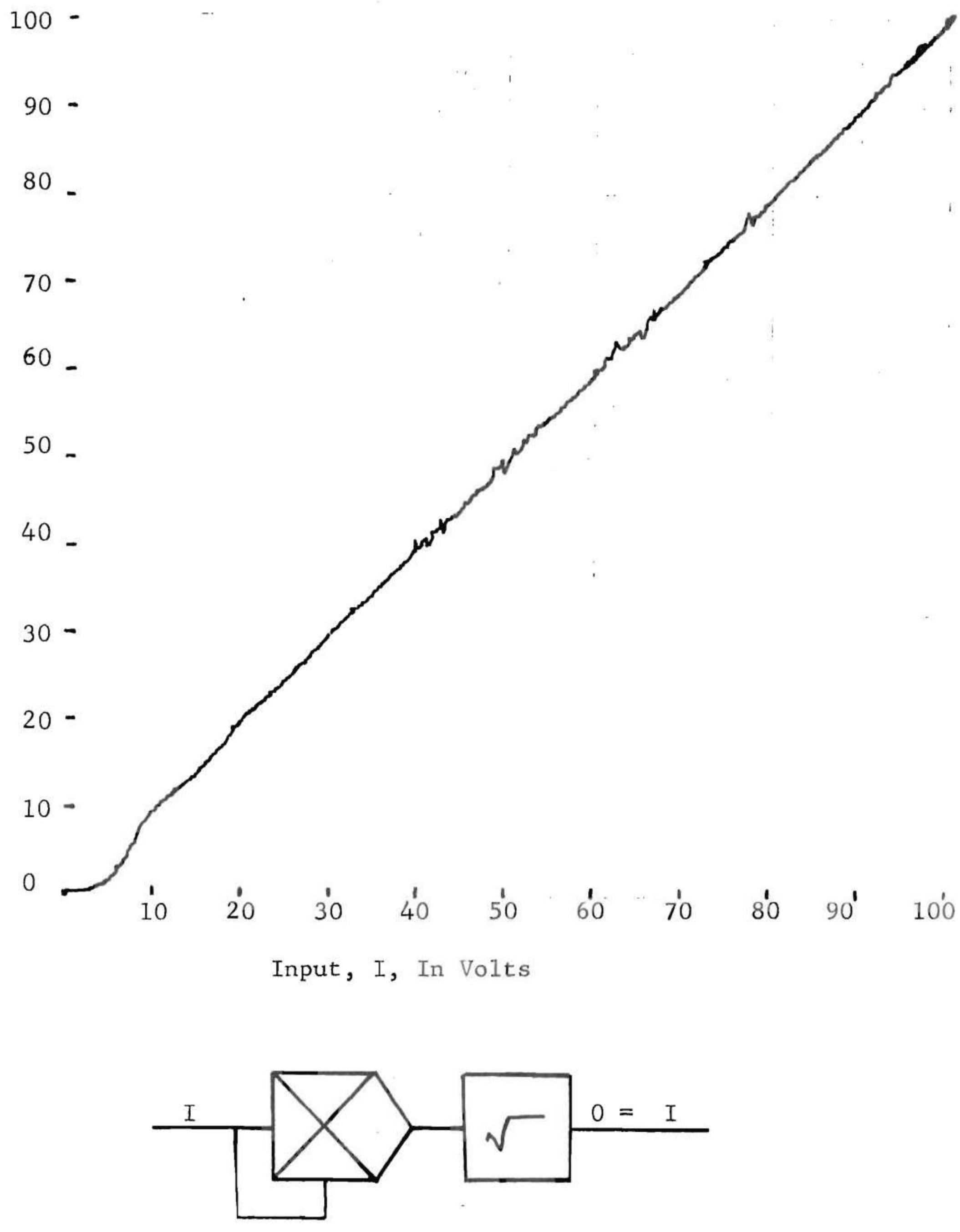


Figure 30. Input-Output Plot of the Squarer and Square Root Devices Connected in Series.

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BIBLIOGRAPHY

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